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This thesis examines radial growth, morphological characteristics, and mean sensitivity among six longleaf pine tracts in North Carolina. The six sites, two from each of the three physiographic regions within the longleaf pine range (Piedmont, Sandhills and Coastal Plain) form a regional transect that tests tree-stand characteristics by site and region. Two core samples and additional measurements of tree diameter, height, and needle length were recorded for 15 trees per site. From the samples collected, measurements in total and latewood ring-width as well as maximum latewood density were used to assess climate/growth relationships. Significant differences between regions were observed for needle length, diameter at breast height, and tree height by region using multi-factor ANOVA. Additionally, significant correlations were observed for latewood ring-width for June-October average precipitation, summer and June–October average temperature with maximum latewood density, and for average June-October Palmer Drought Severity Index and latewood ring-width. Interseries correlation was significantly lower for the Coastal Plain region, and mean sensitivity was significantly lower for the Piedmont region.

COMPARING GROWTH AND MORPHOLOGICAL CHARACTERISTICS OF NORTH CAROLINA LONGLEAF PINE STANDS

by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

1.1 Objectives

This thesis examines radial growth and morphological characteristics among six longleaf pine stands within North Carolina and addresses two questions. First, do significant differences in total and latewood radial growth, maximum latewood density and mean sensitivity exist amongst longleaf pine stands: And if so, are there detectible environmental characteristics such as soil type and climate that cause such spatial variation? Second, do spatial patterns exist in tree morphology that may reflect the influence of edaphic conditions or environmental pressures such as canopy competition or exposure to hurricane-force winds? My null hypothesis is that no significant differences exist in climate-growth relationships, maximum latewood density, and morphological characteristic variability among different sampling locations. Herein, I examine these questions and discuss their implications.

1.2 Background on longleaf pine

1.2.1 Geographic Distribution

Prior to European settlement, longleaf pine was the dominant pine species of the coastal southeastern United States ranging from southern Virginia to eastern Texas (Brockway & Outcalt, 1998; Frost, 2006). Longleaf pine forests are among the most

biologically diverse ecosystems in North America, supporting hundreds of plant and animal species (Ramsey *et al.*, 2003). Early settlement accounts note expansive tracts of longleaf pine dominating various topoedaphic environments that span across seepage wetlands, mesic flatwoods, and higher sandy and clay ridge crests near the Gulf of Mexico and Atlantic coastlines (Davis, 1996). The species' range has diminished from approximately 33 million ha to 776,000 ha (Way 2011) principally due to anthropogenic processes, which include fire suppression, logging, species conversion, and domesticated animal grazing (Brockway & Outcalt, 1998). The greatest reduction in areal coverage occurred in a 200-year period from European settlement to the mid-1900s, accounting for a contraction of the longleaf pine ecosystem from dominating 93% of the Southeast to less than 2 % at present (Davis, 1996). Few isolated forest stands remain with only a dozen known old-growth tracts (Davis, 2006). Longleaf pine forests are among several highly endangered ecosystems in North America and their loss of historical habitat coupled with their ability to support hundreds of herbaceous species makes it one of the most biologically diverse and endangered habitats on Earth (Noss *et al.*, 1995).

1.2.2 Literature Review

The majority of the available literature discussing the various studies, observations, and accounts of longleaf pine begin by focusing on the reduction of the species range from the first European settler's accounts to today (Noss *et al.*, 1995; Brockway & Lewis, 1997; Varner & Kush, 2004; Van Lear *et al.*, 2005; Davis, 2006; Frost, 2006; Way, 2011). The reduction of the species range has declined from approximately 33 million hectares to less than 1 million hectares, a 97% reduction in

range from the species' historic extent. Longleaf pine's formal range dominated the coastal plain from southeast Virginia to eastern Texas, extending into the Piedmont, Cumberland Plateau, and the Blue Ridge physiographic regions. The extension of longleaf pine's range was explored by Outcalt and Sheffield (1996) where they proposed the upland range may have doubled the species' supposed extent to that of around 60 million ha. This range reduction was not an entirely intentional act, however, but rather an insufficient understanding of the management requirements of the longleaf pine ecosystem (Van Lear *et al.,* 2005).

Longleaf pine ecosystems are fire dependent, for which the recurrence of cool ground fires is vital to the species health, regeneration, and maintenance (Sullivan *et al.,* 2003; Varner & Kush, 2004; Frost, 2006). Fires, both natural and prescribed, serve as a tool for the reduction of forest fuels, enhancing wildlife habitat, improving grazing land, thinning overstocked stands, disease and insect control, site preparation for restoration, and fire-adapted ecosystems maintenance (Sullivan *et al.,* 2003). The longleaf pine ecosystem evolved to withstand ground fires, and benefits in various ways from the frequently burned landscape. Longleaf pine trees benefit from both low interspecific and intraspecific competition (Palik *et al.,* 2002). Frequent fires eliminate the presence of tree species that can occupy the region, including loblolly and shortleaf pine, as well as various hardwoods that invade longleaf pine forests if not burned on a 1–5 year interval (Haywood *et al.,* 2001; Davis, 2006). Several morphological characteristics are exhibited by longleaf pine that indicates their fire-dependence relationship. Sloughing bark at the

tree's base protects the inner cambium from the frequent ground fires (Figure 1.2.2a), and long needles serve as a ground fuel enhancer (Hare, 1965; Means, 1985).

Figure 1.2.2a. Thick bark accumulating at the base of a longleaf pine at Jones Lake State Park provides heat protection to the cambium during ground fires. Photo by Lindsay Cummings

The paucity of low-lying branches keeps ground fires from spreading to the trees' crown (Schwilk & Ackerly, 2001). Taproots that begin as thick as the trunk and gradually taper can penetrate water sources 2–3 m below ground, serving as both a nutrient store if the young tree is burned in its grass stage and as an adapted drought resistant tool. Once fire has reduced the fuel load and cleared the ground of competitive plants, seedlings of the longleaf pine can easily establish on the bare mineral rich soil. The characteristics that

allow longleaf pine to endure frequent disturbances also reinforce site dominance, which may partially explain why the species can live up to 500 years (Brockway & Outcalt, 1998; Frost, 2006).

Longleaf pine is a keystone species of the Southeastern U.S. (Means, 2006), and their prevalence has allowed for many plant species in the landscape to be dependent upon its ability to enhance and distribute fire. Means (2006) and Outcalt (2008) address the many locally, endemic plants and animals that have evolved with longleaf pine's fire regime. Their studies note when fire suppression is practiced, many of the co-occurring species of the longleaf pine forest lose their ability to reproduce and become locally absent. Further, ground fires offer protection against pest infestations, especially the black turpentine beetle, *Dendroctonus terebrans* (Sullivan *et al.,* 2003). The buildup of forest-floor debris enhanced beetle infestations, thus fire's ability to control pest populations can significantly reduce pest related tree-mortality in longleaf pine forests (Sullivan *et al.,* 2003).

Species that cohabitate the region include a variety of wiregrass species and many prostrate woody shrubs that are endemic to the longleaf ecosystem (Harrington, 2006). This longleaf pine-wiregrass ecosystem is but one of several classifications that Peet (2006) outlines as the major landscapes of longleaf pine forests. Peet's classifications are driven by soil texture and moisture regimes and is guided by the percent silt found in the A horizon. This classification is as follows: hydric to mesic ultisols support savannas whereas mesic to sub xeric ultisols create a well-drained habitat to form the silty uplands. Hydric to mesic spodosols create the flatwoods region, whereas

more subxeric entisols create the sandy uplands. The driest super-xeric entisols support the sand barrens and sandy uplands. This classification works well for the Coastal Plain, yet is inoperative when observing the Piedmont and montane longleaf types, where the dependence on soil-moisture lessens and is superseded by percentage clay and silt as well as incident solar radiation (Pete, 2006).

Of the hundreds of plant and animal species endemic to longleaf pine ecosystems, 30, including the red-cockaded woodpecker and the gopher tortoise, are federally listed as either threatened or endangered (Landers, 1987). Hardin & White (1989) observed 191 rare plants in the longleaf pine-wiregrass ecosystem, 122 of which are considered rare or threatened throughout their range. Means (2006) sampled and listed the 212 resident vertebrate species found exclusively or primarily in longleaf pine ecosystems and determined faunal diversity was the greatest for all temperate North American forests, which results from the antiquity of the type of ecosystem and its historical range. Further, 38 of these species are specialists that only inhabit longleaf pine savannas. Despite the prodigious biological diversity, these studies conclude that a fire frequency cycle replicating what would have occurred prior to suppression activities is paramount for species preservation and ecosystem health.

Prescribed burns are the first and most critical tool in longleaf pine forest management (Haywood *et al.*, 2001; Schwilk & Ackerly, 2001; Karmachary *et al.*, 2012). Various silvicultural methods exist that seek to emulate natural-system disturbance, many of which are described by Pakik *et al.* (2002) as possible methods for longleaf forest management. Management styles that best replicate natural disturbances, introduce

frequent ground fires, and create adequate canopy gaps may be most effective (Palik *et al.,* 2002). The findings of Brockway and Outcalt (1998) stress the importance of creating and maintaining canopy gaps for longleaf pine ecosystem regeneration. Being a shade-intolerant species, young longleaf pines only grow in peripheral gaps between adult longleaf pines. Saplings may take root underneath parent trees, however, lower light levels within the understory coupled with excessive needle litter that produce hotter fires directly below them restrict their growth. In fire-suppressed forests, canopy gaps become infiltrated by broadleaf and other pine species, therefore, gap formation and management is critical to creating the needed requirements for longleaf pine regeneration.

Several anthropogenic actions have led to the reduction of the longleaf pine landscape since post-European settlement. Such actions include the naval-stores industry, excessive logging, and forests-to-farmland conversion (Frost, 2006). These actions coupled with fire suppression and replanting with quick-growing pines such as shortleaf and loblolly have further reduced longleaf pine's dominance. The naval-stores industry, a term used to comprise the industries that produced and exported rosin, turpentine, and tar from mostly longleaf pine pitch, began at the northern extent of the species range in Virginia in the early 1600s (Frost, 2006). Longleaf pine trees were vital to the naval stores industry for their abundance and resin content, which Mohr (1896) notes as being the highest of any pine. Documents dating to AD 1609 are some of the earliest accounts of the Jamestown, Virginia colony exporting several dozen barrels of pine products to England (Frost, 2006). Both tar and pitch were essential products to daily life in early American years, as they were used for various applications including sealing wooden

ship hulls, coating sails, and greasing wagon axels (Frost, 2006). The industry climaxed in the early 1800s with the introduction of the copper still, allowing the final product to be shipped internationally in its distilled form. The utilization of the copper still influenced the largest expansion of the industry, exploiting nearly all virgin and old-growth longleaf pine sites until its demise in eastern Texas by 1900. Box-scarring the trees may not affect growth or lumber quality as the heartwood remains, but the voids created by scarring allow for pest intrusion and a weakening of the tree's high-wind and fire resistance (Mohr, 1896). Mohr's work centered on the idea that logging would follow turpentining within a decade; however, as many deformed box-faced trees remain today his statement was not supported fully by actual events.

The naval stores industry expansion during AD 1750–1850 coincided with the largest incursion of settlers and immigrants into longleaf pine forests, who converted forests with fertile soils to farms aided by the introduction of the steam-powered saw-mill. Forests that escaped turpentining and logging were decimated by feral hogs introduced by early settlers, which ate the young longleaf pine saplings in the grass stage of development. Frost (2006) cites early agricultural census data on free-ranging hogs in North Carolina and Virginia ranging from 10,000–40,000 hogs per county. The hogs are attracted to longleaf pine during the grass stage development, (0–7 years), where the roots are sought for their sugar and starch concentrations. In such dense populations, and with the ability to uproot and consume anywhere from 200–1000 longleaf pine saplings daily, the influence that wild hogs had on longleaf pine forests was significant. Such ecologically negative resource-dependent actions from early settlers were unknown until

much of the landscape had been rid of longleaf pine by the early 1900s (Frost, 2006). The early 1900s forestry management of fire suppression, coupled with the replanting of loblolly and shortleaf pines, brought the near demise of longleaf pine and has reduced the species' range to its current extent.

As of 2013, few substantial, well-maintained remnants of longleaf pine communities exist, and their management often relies on effectively maintained fire regimes (Frost, 2006). Well-maintained examples can be found on military bases, national and state lands, and on private reserves. Frost surveyed 785 longleaf pine forest stands during 1978–2003 and found that by the beginning of the 21st century only 19% of the northern range (Carolinas and Virginia) of longleaf pine stands were maintained by fire, and only 9% retained something approaching the full complement of plant species that they once supported under natural fire regimes (Frost, 2006). Furthermore, once fire had been reintroduced into land management strategies, the recovery of the herbaceous layer harboring the bulk of the floristic diversity (Outcalt, 2000) was slow, taking decades to establish (Frost, 2006). Presently, less than 97,000 ha of the species original extent remains in good enough condition to support native plants and animals (Outcalt, 2000). A sizable contribution of the literature acknowledges the urgency of the dwindling longleaf pine ecosystem and the various approaches that must be undertaken to preserve the current tracts as well as restore the landscape to its previous state (Hardin & White, 1989; Noss *et al.*, 1995; Means, 1996; Van Lear *et al.*, 2005; Frost, 2006).

Despite the species large geographic range, research to understand climatic effects on longleaf pine growth suggests the primacy of warm-season precipitation, with

temperature and cool-season precipitation having minor contributions. Henderson and Grissino-Mayer (2008) observed multi-century climate relationships for longleaf pine at multiple sites throughout the species' range. The researchers found that all dendrochronological research using longleaf pine has been fairly consistent with respect to moisture response in the growing season, but inconsistent with respect to temperature response and lag effects. The lag effect is attributed to differences in soil types that longleaf pine inhabits, confirming previous longleaf-climate research results. Several studies on climate and longleaf pine emerged in the 1930s using stands in northern Florida and southern Georgia (Lodewick, 1930; Coile, 1936; Schumacher & Day, 1939). Lodewick (1930) found no relationship between radial growth and temperature, but found a strong positive correlation between radial growth and current-year rainfall. Coile (1936) found a negative correlation between radial growth and August temperature, and a positive correlation with early spring rainfall. Later, Zahner (1989) found that radial growth was negatively affected by summer Palmer Severity Drought Index (PDSI) in southern Alabama. The PDSI, first published in 1956, is a soil moisture measure based on both precipitation and temperature. The PDSI measures long-term, cumulative drought cycles; therefore, the intensity of drought during a current month is dependent on the current weather patterns plus the cumulative patterns of previous months. PDSI values less than -2 indicate drought conditions, with more negative numbers indicating greater drought severity (State Climate Office of North Carolina, 2013). Other researchers that have found relationships with radial growth and PDSI including Devall *et al.* (1991), who found the best predictors for radial growth of longleaf pine included August precipitation,

September temperature, and February PDSI. Devall *et al.* (1991) also noticed the influence of hurricane passage, with a surge in growth in 1969 following the passage of hurricane Camille that year. Meldahal *et al.* (1999) found March and September rainfall had the greatest effect on total ring width, and while latewood mean sensitivity was higher than total and early wood ring widths, it correlated stronger with all climate parameters. In Florida, Foster and Brooks (2001) studied both slash and longleaf pines' response to precipitation and water availability across a hydrologic gradient, from mesic flatwoods to xeric sandhills. They found that spring and summer precipitation had positive correlations with radial growth for both species on the higher elevation xeric sites, with previous summer precipitation being a better indicator of growth for the intermediate-elevation sites. While much research on longleaf pine centers toward the lower region of the species range, research is lacking towards the Northern extent (Bhuta *et al.,* 2009). Bhuta *et al.* (2009) tested whether longleaf pine stands at their northern extent were more responsive to winter temperatures than stands at southern sites. Differing from studies at other areas of longleaf pine's range, Bhuta *et al.* (2009) found that southern Virginia sites respond positively to winter precipitation and temperature, and negatively to previous August PDSI, suggesting winter temperatures are more influential at a species northern longitudinal range limit. Henderson and Grissino-Mayer (2008) note the importance in collecting data from multiple sites for tree-ring/climate research in that subtle differences in tree growth can occur due to both site heterogeneity and intraspecies variability in climate response, as noted in a study of shortleaf pine in Georgia (Grissino-Mayer & Butler, 1993).

Studies of tree growth response to both latitudinal and longitudinal gradients have been undertaken for a variety of species. Hofgaard *et al.* (1999) studied climatic response for black spruce (Picea mariana) and jack pine (Pinus banksiana) over a latitudinal gradient in western Quebec. They found that summer temperature and previous years' May precipitation were the main climatic variables responsible for site definition along their gradient. Cook *et al.* (2001) studied a variety of oaks, pines, and beech species over a latitudinal gradient in Louisiana and Texas. Only on the xeric western range limit of the species did location override genetic grouping differences, indicating that climate responses based on genetics are more important than ecological and site characteristics in determining the tree-ring patterns of the sampled species overall (Cook *et al.*, 2001). A third study by Pederson *et al.* (2004) studied six tree species on the Hudson River Valley region. They found winter temperature was the greatest limitation on growth, and that growth response to winter temperature is both species and phylogenetically specific. Further, they indicate that the influence of temperature on radial growth at species and ecosystem levels may operate differently at varying geographic scales (Pederson *et al.*, 2004). Few studies measure climatic response of a single species along a latitudinal/longitudinal gradient, and no studies at present undertake such a study for longleaf pine. Realizing the lack of geographic and genetic studies on longleaf pine, Schmidting and Hipkins (1998) conducted a provenance study, measuring the amount of genetic variability based on allozyme diversity throughout the longleaf pine range. They found longleaf pine has less overall genetic diversity than other southern pines, and that genetic diversity decreases longitudinally from Texas eastward. This finding supports a

hypothesis that longleaf pine occupied a refuge in southern Texas and northern Mexico during the Pleistocene, and has since expanded East and North where populations are both younger and less genetically diverse (Schmidtling & Hipkins, 1998). Their findings confirm the work of Wells and Wakeley (1970) who found through provenance testing that significant variation in growth, survival, and disease susceptibility in longleaf pine exist from samples taken from gulf coast states. Latitudinal and longitudinal differences in guard cells, interstomatal spacing, and stomatal distribution per unit area of needle exist in longleaf, with guard cell size increasing, and interstomatal space decreasing, from north – south, and from west – east (Anoruo & Blake, 1997). Anoruo and Blake (1997) also found a similar pattern with stomatal concentration per unit area of needle, decreasing from north – south, and from west – east.

CHAPTER II

METHODOLOGY

2.1 Discussion of sites

Sites in North Carolina were selected as they contain known old-growth stands and are located near the northern extent of the species' range. The importance of selecting old-growth sites are that populations within them attain old age of >150 years with minimal disturbance, therefore exhibiting pre-European settlement conditions. The six sites selected (Figure 2.1a) span the longleaf pine's range from the coastal plain inland, with two sites selected from each physiographic region of the species' range.

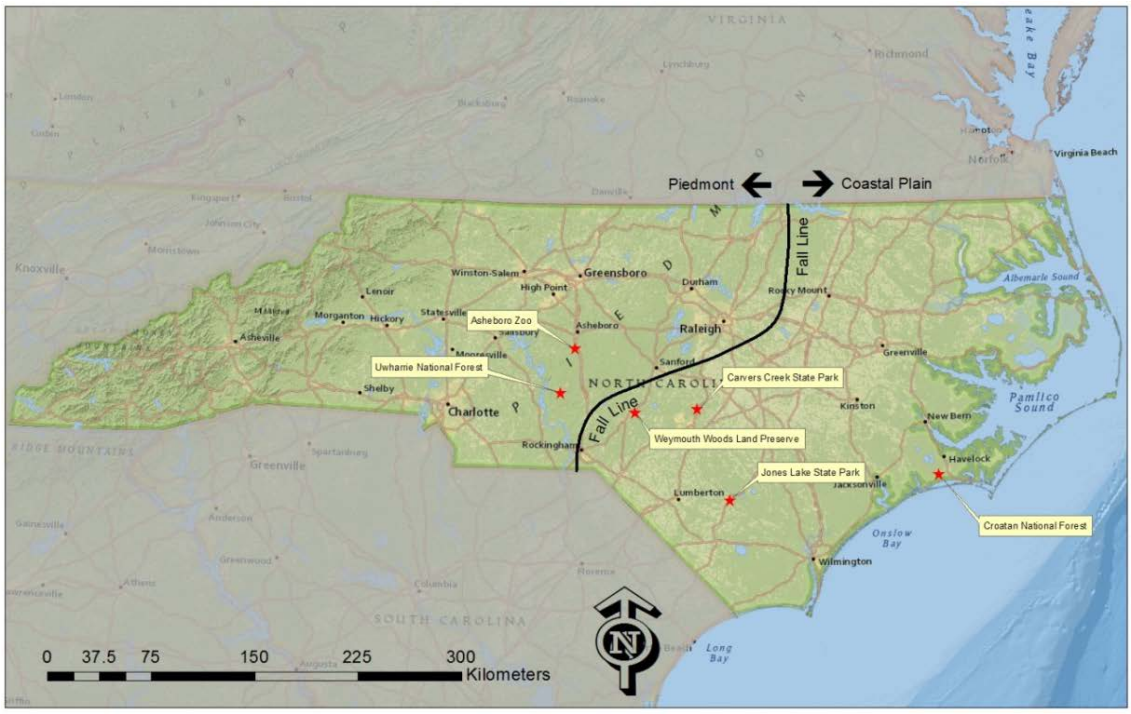

Figure 2.1a. Map of field sites.

2.1.1 Piedmont sites

Roberdo Tract: The Roberdo tract, located in Montgomery County 8.8 km southwest of Troy, is maintained by the Uwharrie National Forest. State Highway 109 divides the tract, and I sampled equally from both sides of the roadway. The tract is under an active burn regime as evident by an open understory with charred bark found on all trees. Longleaf pine dominate the sampling area with ages of trees ranging from <100 years for the west side of the highway to 100+ for the east side of the highway. Herndon silt loams are the dominant soil series. Areas of the Uwharrie National Forest have been reforested as much of the area had previously been farmed. Replanting was not evident in

the Roberdo sampling area, however, tree ages were the youngest of the six sites indicating a second-growth forest.

Nichols Tract: The Nichols tract, named after the property's previous owners, was purchased by the North Carolina Zoo in 2011. The site, now named as the Arnett Branch longleaf pine forest, is located in Montgomery County 11.3 km north of Troy. Known for being the largest remaining stand of old-growth Piedmont longleaf pine in North Carolina, the property was purchased by the Land Trust for Central North Carolina and the N.C. Zoo for plant preservation and environmental education. A mix of longleaf pine and piedmont broadleaf trees dominate the tract, and the soil series is a combination of Herndon silt loams and Georgeville silt loams. Evidence of the naval stores industry and logging, followed by fire suppression, can be seen in older trees with cat-faced scars, large stumps, and a dense understory. Fire was purposefully reintroduced in February 2013 as a management strategy.

2.1.2 Sandhills Sites

Weymouth Tract: The 364 ha Weymouth Woods-Sandhills Nature Preserve is adjacent to the community of Southern Pines, named after the abundance of longleaf pine trees dominating the region. Formally owned by the Boyd family, the land was purchased early in the 20th century to protect old-growth timber from logging, and was named Weymouth Woods for its resemblance to Weymouth, England. Acquired by the state in 1963, the Boyd tract was the first natural area in the N.C. park system. Mature and old-growth longleaf pine inhabit the tract, containing the oldest known living longleaf pine

dating back to the 1548 (Wireback, 2008). Loamy sands of the Ailey and Vaucluse series dominate the tract and prescribed burning is limited to specific areas.

Carver's Tract: Carver's Creek State Park is an addition to the N.C. State Parks system, purchased by the state with help from the Nature Conservancy from James Stillman Rockefeller and will officially open once facilities are constructed in 2013. The former estate located 16 km north of Fayetteville, is comprised of 574 ha acres of longleaf pine forests, mature mesic hardwoods, swamp forests, and steep bluffs. Sampling locations were located along ridgelines where a combination of loamy sands of the Glead, Candor, and Blaney series dominate the sampling area. Located east of the Piedmont-Coastal Plain fall-line, the area supports a maintained longleaf pine-wiregrass ecosystem as noted by evidence of recent burning.

2.1.3 Coastal Plain Sites

Salters tract: Jones Lake State Park is located in central Bladen County 5.6 km Northeast of Elizabethtown. The park opened in 1939 as the first state park for African Americans, and contains two naturally occurring Carolina bays, Jones Lake and Salters Lake. The once fertile, drained lowlands became marginal for farming due to poor conservation practices, and the land was purchased by the state through a New Deal initiative. Bay and pocosin vegetation dominate the hydric areas of the park, with longleaf pine and turkey oak forests located on the higher-elevation sands. Sands of the Leon and Kureb series dominate the sampling area, and prescribed burning is practiced as evident by the open understory.

Millis tract: Millis-road tract, named for the corridor from the town of New Bern located 32 km north, is one of the several known old-growth tracts of longleaf pine in North Carolina. The open savanna-longleaf pine ecosystem is maintained by the Croatan National Forest. The savanna-pocosin ecosystem bares characteristics of longleaf pine ecosystem biodiversity noted by carnivorous plants, native flowers, and red cockaded woodpeckers. Located 8 km from the Atlantic Ocean, the Millis tract is the most "coastal" site of the six. Soils of the sampling areas are of the Leon sand series, and the site is under an active prescribed and natural fire regime.

2.2 Sampling procedures

At each site, samples were collected from 15–20 healthy trees. Trees unsuitable for the study include those with visible fire and turpentine scars, visible rot, partially or fully dead crowns, or any other deformation that may affect growth response as radial growth. Unsuitable trees were excluded as radial growth may be affected from trauma caused by turpentine scarring, wind/ice damage, and rot. In assessing trees, bias towards older trees, which exhibit such characteristics as flat-topped crowns, gnarly trunks, and overall robustness in trunk size or height (Figures 2.2a and 2.2b) was taken.

Figure 2.2a. Old-growth trees at the Millis tract in Croatan National Forest. Longleaf savanna dominate the foreground ridge with pocosin vegetation in the background. Photo by Thomas Patterson.

Figure 2.2b. An old-growth longleaf pine amongst turkey oak at Jones Lake State Park. Photo by Lindsay Cummings.

Furthermore, trees with active red-cockaded woodpecker nests were avoided as to not interfere with the sensitive bird species. For each selected tree, tree height (m) was measured with a digital rangefinder and diameter (cm) at breast height (DBH) was measured with DBH tape. Two core samples were removed from opposing sides of each

tree using a 5.15 mm Swedish increment borer for a total of no less than 30 samples per site. Each tree was geographically marked with a handheld GPS unit. Lastly, five fascicles each containing three leaves, were gathered at random directly below each sampled tree. Each needle cluster was measured from bud to tip for the longest needle in mm, recorded, and returned to the forest floor.

2.2.1 Processing, cross dating, and measurement

All samples were air dried for greater than 24 hours then mounted to wooden strips with wood glue. Once dry, the samples were sanded with a progressively finer grit (120, 220, 320, 600) until each sample cell structure is visible to help distinguish ring boundaries. Once all samples were sufficiently sanded, each sample was cross-dated using the list method. This process allowed for the detection of the tree's age as well as identification of false and or missing rings. Post cross-dating, samples were measured using the computer program WINDENDRO. From WINDENDRO, measurements of total ring-width (TRW), latewood ring-width (LW), and maximum latewood density (MXD) were obtained. While TRW and LW is measured to the 0.001 mm, MXD is estimated in g/cm^3 using a reflected-light method where higher density values are returned when latewood is darkest. TRW, LW, and MXD measurements were selected as previous research has found TRW and LW correlate with precipitation and drought (Lodewick, 1930; Devall *et al.*, 1991; Meldahl, 1999; Foster & Brooks, 2001; Henderson & Grissino-Mayer, 2008; Bhuta, *et al.*, 2009) and MXD has been proven as a useful proxy for warm season temperature (Chen *et al.*, 2012). At present, MXD analysis has

not been undertaken for longleaf pine, and this study is the first to use this measure for climate analysis.

2.3 Analysis

2.3.1 Statistics and standardization

I used two programs for chronology statistics and standardization. COFECHA aided in cross-dating efficiency, accuracy, and provided site chronology statistics. ARSTAN was used to detrend and standardize all site chronologies. The standardization procedure produces chronologies by detrending and indexing the series to account for age-related radial growth decline, inherent in trees (Cook & Holmes, 1985). A cubic smoothing spline with a 50% threshold was applied to each location's TRW and LW chronology, as this standardization has been used successfully by Henderson and Grissino-Mayer (2009) with longleaf pine/climate relationships. From this procedure, I opted for the STANDARD chronology, as opposed to the RESIDUAL or ARSTAN, for my final chronologies as preliminary analysis exhibited higher correlations with climate variables for the STANDARD chronology over the alternatives.

2.3.2 Morphological standardization techniques

I chose to standardize my morphological data by tree age in order to control if a relationship between age and morphological characteristics exists. This technique involved taking the variable of interest and dividing it by each tree's age inferred by the first year of growth from each sample. Some samples I achieved pith, therefore I was able

to account for every growth ring. All other samples I achieved curvature, missing up to a decade of growth rings due to sampling error. I have controlled (minimized) for any standardization error which may occur from under estimating age by obtaining a large sample size per tract (n = 30). The following three formulae were used to standardize needle length, DBH, and height:

$$\frac{tree\ average\ needle\ length}{tree\ age\ at\ 1.4\ m} = standardized\ needle\ length$$

$$\frac{tree\ DBH}{tree\ age\ at\ 1.4\ m} = standardized\ DBH$$

$$\frac{tree\ height}{tree\ age\ at\ 1.4\ m} = standardized\ tree\ height$$

R, a statistics package, was used for all statistical analysis. My hypotheses test for differences between tracts, therefore procedures that test for differences between more than two groups were undertaken. Multi-factor ANOVA tests with Tukey-Kramer post-hoc procedures measured the differences in means between sites and regions for all morphological characteristics. I tested if correlations were present between the three ring measurements and the climate variables using Pearson's product-moment correlation. Further, I used a modified Z-test (Fisher, 1921) to test if correlations from two independent populations significantly differed using the following formula:

$$z = \frac{r'_1 - r'_2}{\sqrt{\frac{1}{(n_1-3)} + \frac{1}{(n_2-3)}}}$$

$$\text{where } r' = (0.5)\log_e\left[\frac{1+r}{1-r}\right]$$

The modified Z-test follows the principals of a standard Z-test, thus both *p*-vales can be computed from Z values to test if regional correlations differ statistically.

2.4 Additional data

2.4.1 Climate data

Palmer Drought Severity Index (PDSI), temperature, and precipitation values were obtained from the State Climate Office of North Carolina for the last 100 years of the chronologies (1912–2011). Average June–October PDSI values, average June–July (summer) and June–October temperatures, and average summer and June-October precipitation values were correlated with current growth years for the three tree-ring chronologies (LW, TRW, MXD) by location and by region. For regional analyses, I averaged the ring-width values of the two sites in each physiographic region. These climate variables were selected as previous studies have noted the relationship of climate to both LW and TRW (Henderson & Grissino-Mayer, 2008) and for MXD and temperature in various tree species (D'Arrigo *et al.*, 2000; Chen *et al.*, 2012; Gindl *et al.*, 2000). The June–October time period accounts for a longer growth period, which captures if late season climate influence radial growth measures for North Carolina longleaf pine as was found for sites in South Carolina, Florida, and Texas (Henderson & Grissino-Mayer, 2008). The latter period also captures much of the North Atlantic hurricane season (June 1–November 30), which may also influence late-season growth. The six sites and two regions spanned over two climate divisions, Piedmont and Coastal Plain. I analyzed the data using both divisions and assigned Piedmont and Sandhills sites

to the Piedmont division, and the Coastal Plain sites to the Coastal Plain division. I repeat this divisional grouping throughout my analysis unless otherwise noted. Lag relationships were analyzed using previous year's climate variables of interest against current year's growth measure. Climate data for PDSI, temperature, and precipitation of the before mentioned time spans were obtained from the state climate office of North Carolina for the years 1911–2010 to test against the following year's growth (1912–2011).

2.4.2 Soils data

All soils data were obtained from an online GIS tool provided by the USDA. For each location, I created a generalized soil series by summarizing the prevailing soil series and its attributes. While soil profiles may change drastically throughout a sampling area, I attempted to control for soil-type changes through sampling selection (i.e. sampling from trees on similar slopes, not on ridgelines or creek beds). Each region's soil belonged to similar soil textural classes so regional comparisons could be made.

CHAPTER III

MORPHOLOGICAL CHARACTERISTICS

3.1 Results

The assumptions of the ANOVA tests regarding normality and constant variance were met; however, observations were not independent and random due to sampling bias. Since independence was not achieved due to limited and defined tracts, as well as no randomization mechanism employed during fieldwork, results pertain only to the tracts used in the study and inference about all longleaf pine in North Carolina, or throughout its range as a whole, would be inappropriate.

3.1.1 Standardized Needle Length

The ANOVA analysis revealed a significant difference in means among the six tracts ($p < 0.001$, Table 3.1.1a, Figure 3.1.3a) for standardized needle length.Table 3.1.1a. ANOVA results for standardized needle length by location.

Table 3.1.1a. ANOVA results for standardized needle length by location.

ANOVA: standardized needle length by location	DF	Sum of squares	Mean Square	F value	*p* value
Fitted	5	0.5106	0.10213	10.73	4.3e-08 ***
Residuals	89	0.8468	0.00951		

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05

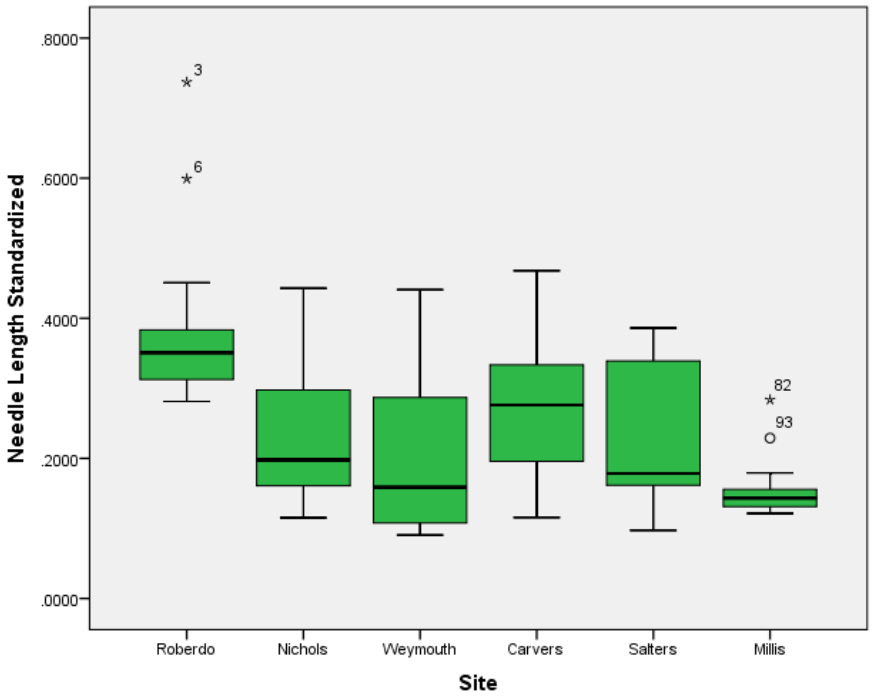

Figure 3.1.1a. Standardized needle length boxplot by location. Each quintile box displays the location's distribution with median line superimposed. Values for needle length are standardized by age. Potential influential-points and outliers are identified by either a circle or star.

All Significant Tukey-Kramer pairwise comparisons ($p < 0.1$) are summarized in Table

3.1.1b.

Table 3.1.1b. Significant ($p < 0.1$) Standardized needle length pairwise comparisons by location.

Standardized Needle Length pairwise comparisons by location				
Comparison	Estimate	Standard Error	t value	*p* value
Nichols - Roberdo	0.138118	0.032975	-4.189	<0.001 ***
Carvers - Roberdo	-0.095757	0.032975	-2.904	0.0511
Weymouth - Roberdo	-0.179347	0.032975	-5.439	<0.001 ***
Salters - Roberdo	-0.143661	0.032975	-4.357	<0.001 ***
Millis - Roberdo	-0.217568	0.033655	-6.465	<0.001 ***
Millis - Carvers	-0.121811	0.036248	-3.361	0.0141 *
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05				

Significant ($p < 0.001$) evidence exists for a difference in means for four comparisons, which compare the Roberdo tract against the Nichols, Weymouth, Salters, and Millis respectively. Evidence exists for a difference in standardized needle length means between Roberdo and Carvers ($p = 0.051$) and between Millis and Carvers ($p = 0.014$). When evaluating the tracts by the regional physiographic grouping variable (i.e., Piedmont, Sandhills, and Coastal Plain,) there was a significant difference in standardized needle-length means between the three regions ($p < 0.001$, Table 3.1.1c, Figure 3.1.1b)

Table 3.1.1c. ANOVA results for standardized needle length by region.

ANOVA: standardized needle length by Region	DF	Sum of Squares	Mean Square	F Value	*p* Value
Fitted	2	0.2518	0.12588	10.47	7.97e-05 ***
Residuals	92	1.1057	0.01202		
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05					

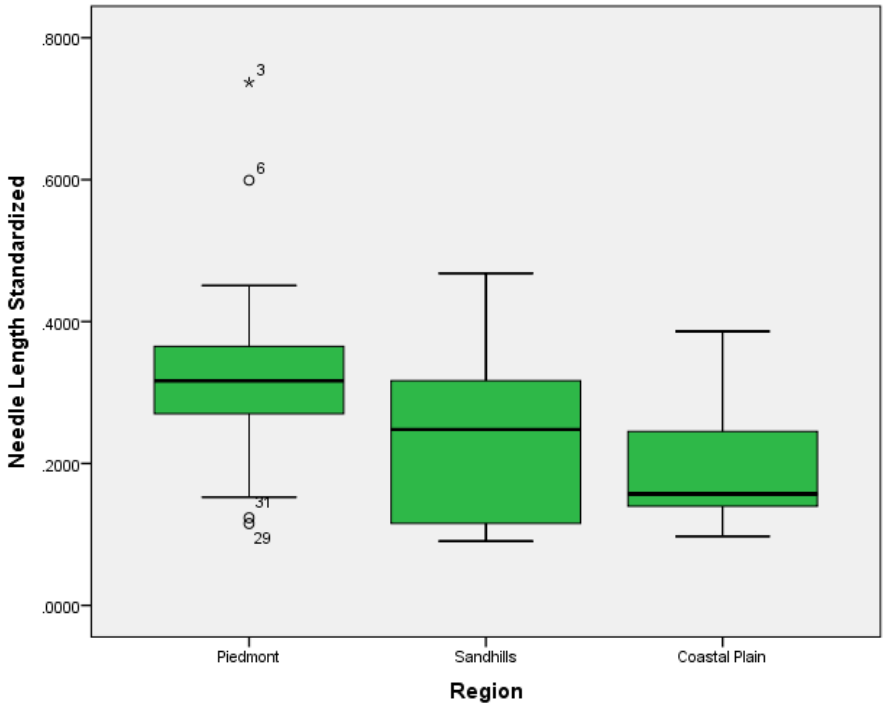

Figure 3.1.1b. Standardized needle length boxplot by region. Each quintile box displays the region's distribution with median line superimposed. Values for needle length are standardized by age. Potential influential-points and outliers are identified by either a circle or star.

Pairwise comparison testing revealed the Piedmont mean standardized needle length was significantly different from both the Sandhills and Coastal Plain regions ($p < 0.001$), but that the Coastal Plain and Sandhills regions did not statistically differ from each other ($p = 0.955$, Table 3.1.1d).

Table 3.1.1d. Significant ($p < 0.1$) Standardized needle length pairwise comparisons by region.

Standardized Needle length pairwise comparisons by region				
Comparison	Estimate	Std. Error	t value	*p* value
Piedmont - Coastal	0.12179	0.02735	4.452	<1e-04 ***

Sandhills - Coastal	0.04179	0.02855	1.464	0.313
Sandhills - Piedmont	-0.08000	0.02710	-2.952	0.011 *
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05				

3.1.2 Standardized DBH

Results of the ANOVA testing indicated a significant difference in standardized DBH means for the six tracts ($p < 0.001$, Table 3.1.2a, Figure 3.1.2a, and Table 3.1.2b).

Table 3.1.2a. ANOVA results for standardized DBH by location.

ANOVA: standardized DBH by location	DF	Sum Sq	Mean SQ	F value	p value
Fitted	5	1.479	0.2959	10.13	1.05e-07 ***
Residuals	89	2.599	0.0292		
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05					

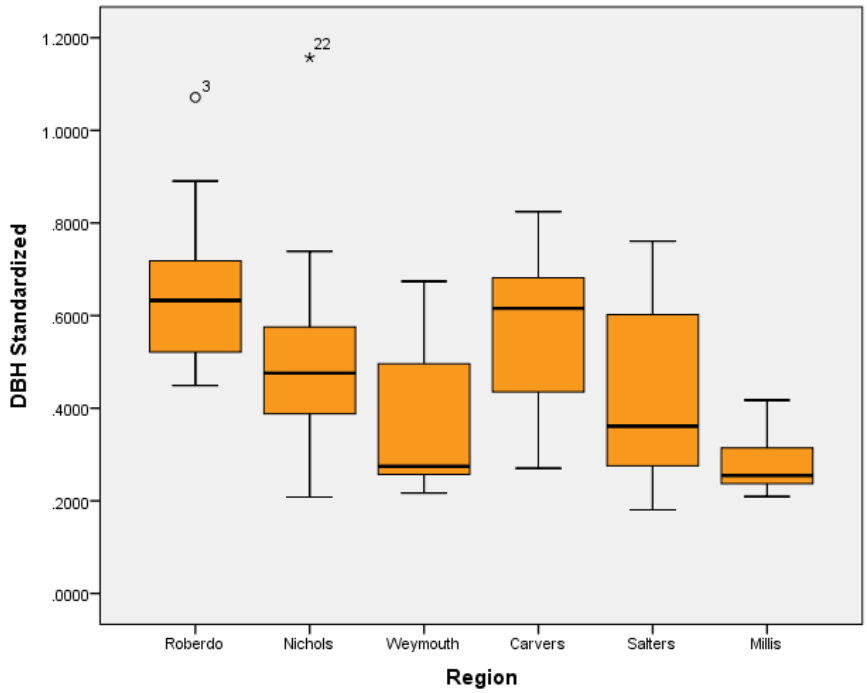

Figure 3.1.2a. Standardized DBH boxplot by location. Each quintile box displays the location's distribution with median line superimposed. Values for DBH are standardized by age. Potential influential-points and outliers are identified by either a circle or star.

Table 3.1.2b. Significant ($p < 0.1$) Standardized DBH pairwise comparisons by location.

Standardized DBH pairwise comparisons by location				
Comparison	Estimate	Standard Error	t value	*p* value
Millis - Carvers	-0.28253	-0.0635	-4.45	< 0.001 ***
Weymouth - Carvers	-0.18979	0.06239	-3.042	0.03523 *
Nichols - Millis	0.22326	0.0635	3.516	0.00874 **
Roberdo - Millis	0.36968	0.05896	6.27	< 0.001 ***
Salters - Roberdo	-0.21581	0.05776	-3.736	0.00427 **
Weymouth - Roberdo	-0.27694	0.05776	-4.794	< 0.001 ***
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05				

Significant ($p < 0.001$) pairwise comparisons include Millis and Carvers, Roberdo and Millis, and Weymouth and Roberdo. Different means existed between Nichols and Millis

(p = 0.009) and Salters and Roberdo (p = 0.004), and Weymouth and Carvers (p = 0.035). Additional region grouping indicated that a significant difference in means existed for the three physiographic regions (p < 0.001, Table 3.1.2 c, Figure 3.1.2b).

Table 3.1.2c. ANOVA results for standardized DBH by region.

ANOVA: standardized DBH by location	DF	Sum Sq	Mean SQ	F value	*p* value
Fitted	2	0.85	0.4251	12.12	2.13e-05 ***
Residuals	92	3.228	0.0351		
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05					

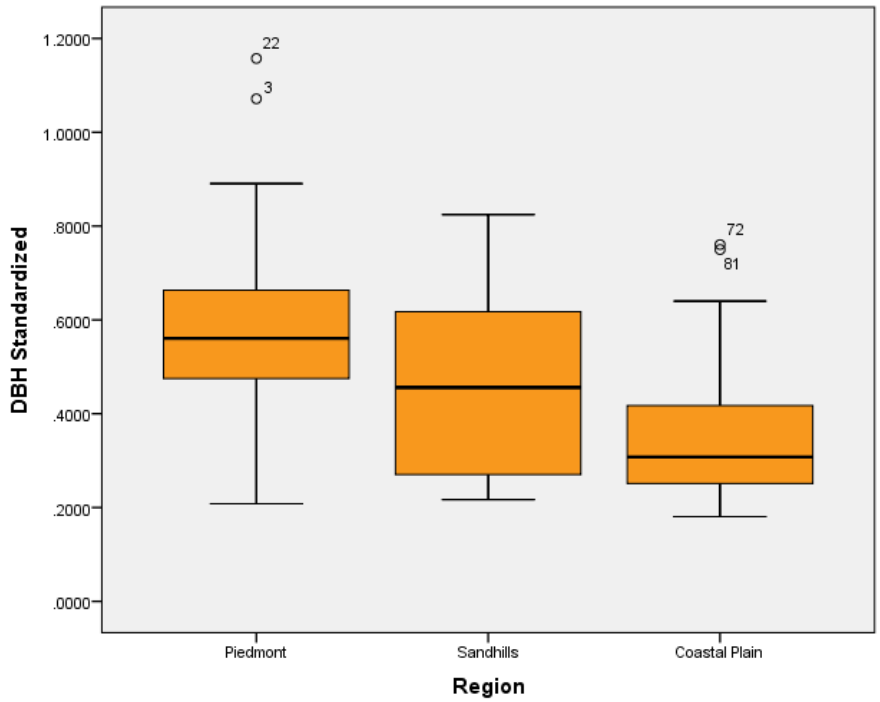

Figure 3.1.2b. Standardized DBH boxplot by region. Each quintile box displays the region's distribution with median line superimposed. Values for DBH are standardized by age. Potential influential-points and outliers are identified by either a circle or star.

Significant pairwise comparisons for standardized DBH (Table 3.1.2d) existed between the Piedmont and Coastal Plain regions($p < 0.001$), Piedmont and Sandhills regions ($p = 0.028$), and between the Sandhills and Coastal Plain regions ($p = 0.074$).

Table 3.1.2d. Significant ($p < 0.1$) Standardized DBH pairwise comparisons by region.

Standardized DBH pairwise comparisons by region				
Comparison	Estimate	Standard Error	t value	*p* value
Piedmont - Coastal	0.22908	0.04674	4.902	<0.001 ***
Sandhills - Coastal	0.10805	0.04878	2.215	0.0739
Sandhills - Piedmont	-0.12103	0.0463	-2.614	0.0280 *
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05				

3.1.3 Standardized Tree Height

ANOVA testing for a difference in standardized tree height among the six stands revealed a statistically significant difference in means ($p < 0.001$, Table 3.1.3a, Figure 3.1.3a).

Table 3.1.3a. ANOVA results for standardized tree height by location.

ANOVA for standardized height by location	DF	Sum Sq	Mean SQ	F value	*p* value
Fitted	5	0.2659	0.05317	11.84	8.67e-09 ***
Residuals	89	0.3998	0.00449		
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05					

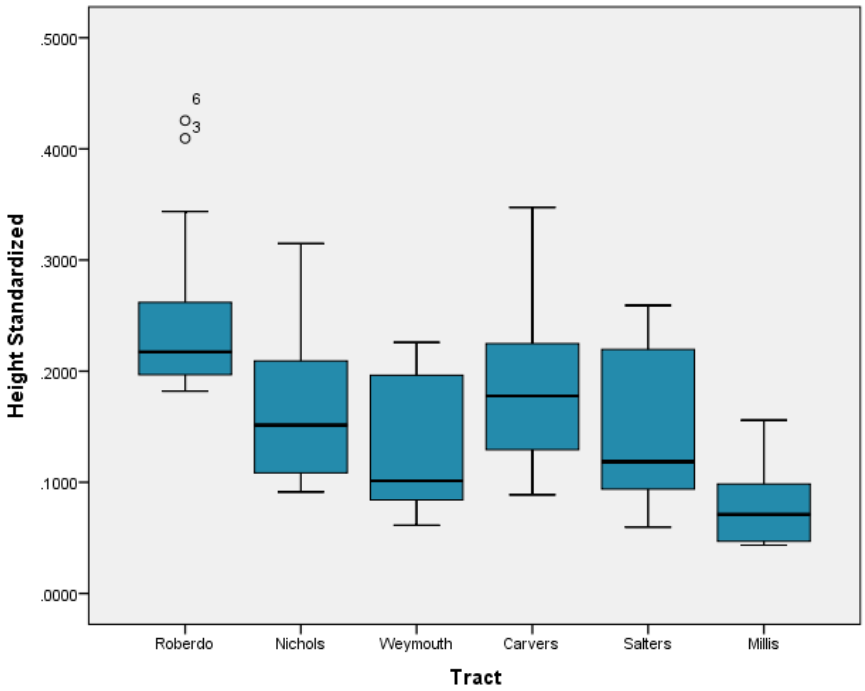

Figure 3.1.3a. Boxplot of standardized tree height by location. Each quintile box displays the location's distribution with median line superimposed. Values for height are standardized by age. Potential influential-points and outliers are identified by either a circle or star.

Significant evidence ($p < 0.001$) existed for a difference in standardized mean tree height between Millis and Carvers, Roberdo and Millis, Roberdo and Salters, and Roberdo and Weymouth (Table 3.1.3b). Evidence existed for a difference in standardized tree height means between Nichols and Millis ($p = 0.009$), Roberdo and Nichols ($p = 0.008$), and between Salters and Millis ($p = 0.054$).0

Table 3.1.3b. Significant ($p < 0.1$) pairwise comparisons for standardized tree height by location.

Standardized tree height pairwise comparisons by location				
Comparison	Estimate	Standard Error	t value	*p* value
Millis - Carvers	-0.10797	0.02491	-4.335	< 0.001 ***

Nichols - Millis	0.08698	0.02491	3.492	0.00947 **
Roberdo - Millis	0.16699	0.02313	7.221	< 0.001 ***
Salters - Millis	0.07182	0.02491	2.884	0.05355
Roberdo - Nichols	0.08001	0.02266	3.531	0.00836 **
Salters - Roberdo	-0.09517	0.02266	-4.2	< 0.001 ***
Weymouth - Roberdo	-0.11217	0.02266	-4.95	< 0.001 ***
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05				

ANOVA testing using the regional grouping showed significant evidence for a difference in standardized tree-height means between regions ($p < 0.001$, Table 3.1.3b, Figure 3.1.3c)

Table 3.1.3c. ANOVA results for standardized tree height by region.

ANOVA: standardized height by region	DF	Sum Sq	Mean SQ	F value	*p* value
Fitted	2	0.1513	0.07565	13.53	7.06e-06 ***
Residuals	92	0.5144	0.00559		
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05					

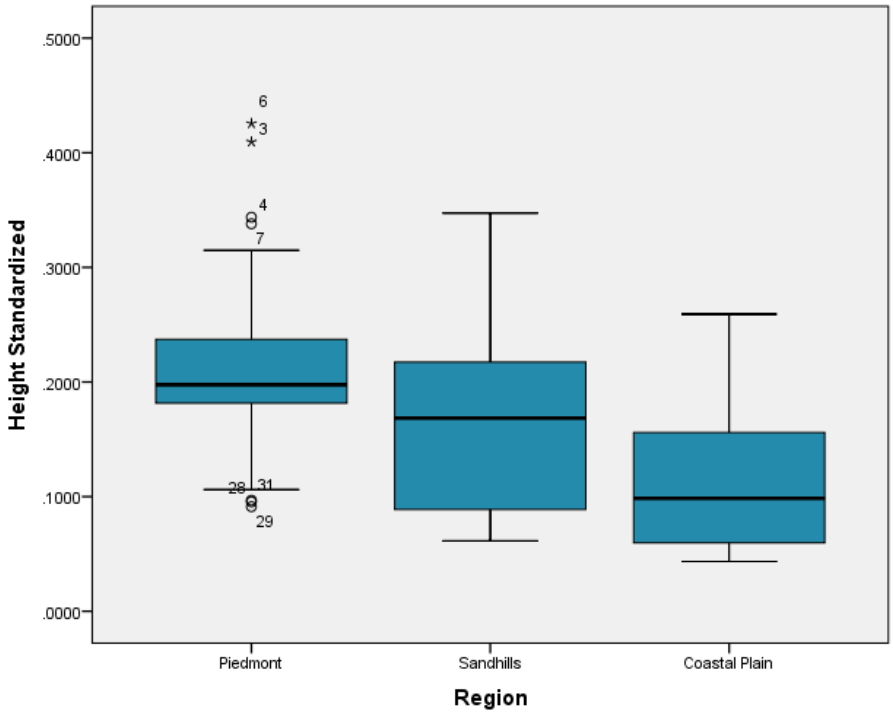

Figure 3.1.3b. Boxplot of standardized tree height by region. Each quintile box displays the region's distribution with median line superimposed. Values for height are standardized by age. Potential influential-points and outliers are identified by either a circle or star.

Pairwise comparisons (Table 3.1.3d) indicated a significant difference in mean standardized tree-height between the Piedmont and Coastal Plain regions ($p < 0.001$), Sandhills and Piedmont regions ($p = 0.016$), and between the Sandhills and Coastal Plain regions ($p = 0.065$).

Table 3.1.3d. Significant ($p < 0.1$) pairwise comparisons for standardized tree height by region.

Standardized tree height pairwise comparisons by region				
Comparison	Estimate	Standard Error	t value	*p* value
Piedmont - Coastal	0.0965	0.01866	5.172	<0.001 ***
Sandhills - Coastal	0.04425	0.01947	2.272	0.0648
Sandhills - Piedmont	-0.05225	0.01848	-2.827	0.0158 *
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05				

3.2 Discussion

Despite an extensive literature review, no analysis of the morphological characteristics across the geographic range for longleaf pine, or for any other southern yellow pine (loblolly, shortleaf, and slash pine), was found in published work. Thus, my study may be the first known attempt to observe changes in needle length, DHB, and tree height for North Carolina longleaf pine stands.

3.2.1 Standardized needle length

Mean standardized needle length significantly differed across the species gradient, with length decreasing from western (interior) to eastern (coastal) locations. Needle length was longest for the two Piedmont sites whereas the Sandhills and Coastal Plain sites expressed no significant differences from one another. The Roberdo tract (westernmost) trees contained the longest mean needle lengths of any site, whereas the Millis site (easternmost) trees had the shortest mean needle length, thus suggesting a distinct pattern exists in needle length based on distance from the coast. Several hypotheses for the presence of longer needles for North Carolina Piedmont longleaf pine may work individually or in concert to explain the geographic variation. First, Piedmont

longleaf pine compete for sunlight in a denser and competitive mixed pine-broadleaf forest thus increased leaf area provided by longer needles may be required to capture sufficient sunlight for optimal photosynthesis (Figure 3.2.1a).

Figure 3.2.1a. Three canopy densities from far left Nichols (dense and competitive) to Weymouth (medium density) to Millis (open canopy). Photo credit L to R: Thomas Patterson, Selima Sultana, Paul Knapp.

As the longleaf pine range transitions from the most inland locations of the Piedmont to the Sandhills, needle length decreased as canopy coverage and broadleaf dominance decreased. Lastly, savanna sites such as Millis are a savanna-grassland community with longleaf pine occurring in park-like stands (Figure 3.2.1a). These Coastal Plain sites contained the shortest standardized needle lengths.

Piedmont soils contain a higher percentage of silts and clays than either Sandhills or Coastal Plain soils that may create favorable conditions for more robust needle growth (Figure 3.2.1b).

Piedmont	**Silt Loams** 50-80% Silt
Sandhills	**Loamy Sands** 0-50% Silt
Coastal Plain	**Sands** 0-10% Silt

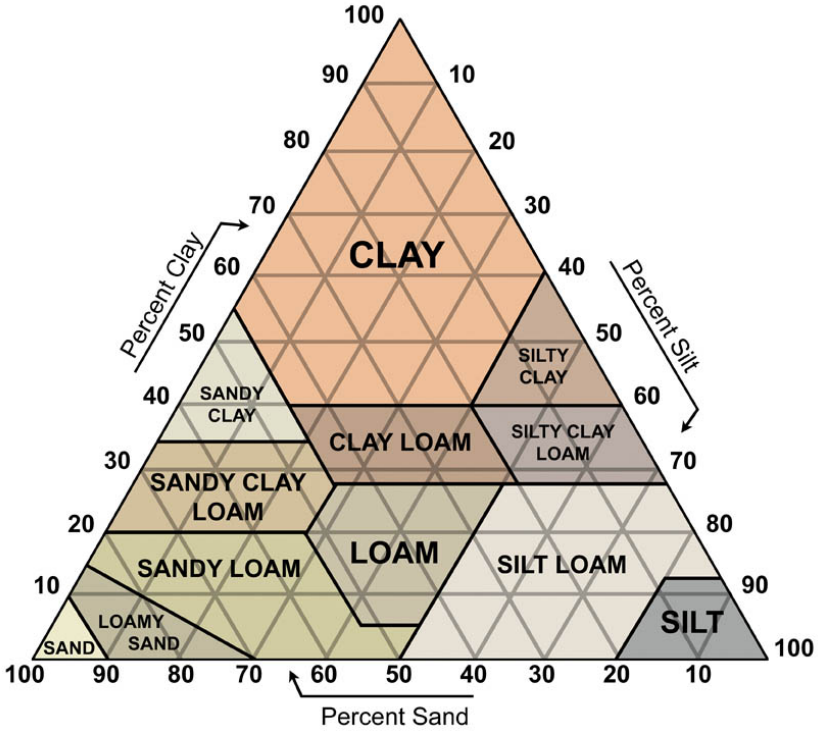

Figure 3.2.1b. Soil texture triangle

Wahlenberg (1946) notes longleaf pine's ability to span less to more fertile soil types of the coastal plain, and the improvement of growth characteristics corresponding with soil enrichment. He concludes longleaf pine may not prefer the less fertile soils, but rather endured these less-favorable edaphic conditions out of necessity not choice. My data support this contention as the Piedmont longleaf pine trees were more robust for all morphological categories measured.

The role of fire is another possibility explaining needle-length differences. Piedmont longleaf pine may produce longer needles to promote 'fire driving'; producing longer needles to increase understory flammability to enhance ground fire. Unlike the Piedmont longleaf pine communities, wiregrasses are common understory species in both the Sandhills and Coastal Plain regions (Figure 3.2.1b) and they serve to produce fine fuels necessary for low intensity (i.e. "cool") fires required for regeneration. In the absence of wiregrass, needles may increase the flammable ground layer to promote ground fire needed for longleaf pine regeneration. Ness (1927) found that longleaf pine typically only inhabit sandy and clayey loams very poor in organic matter because seedlings perish from damping-off during infancy if germination takes place soil containing a large amount of humus. I have found that longleaf pine can exist on locations where conditions would lead to moist humus richness; however, longleaf pine's ability to endure ground fire, which may be supported by flammable needle-fall, has allowed for their co-existence in an otherwise Piedmont broadleaf forest.

Exposure to high winds may also affect needle length. Maximum wind speed from tropical cyclones or depressions typically decrease from the coast to interior portions of North Carolina as the fuel source for such wind-producing events is eliminated as the storm tracts in-land as was the case when hurricane Fran made passage through North Carolina on September, 5th 1996 (Figure 3.2.1c).

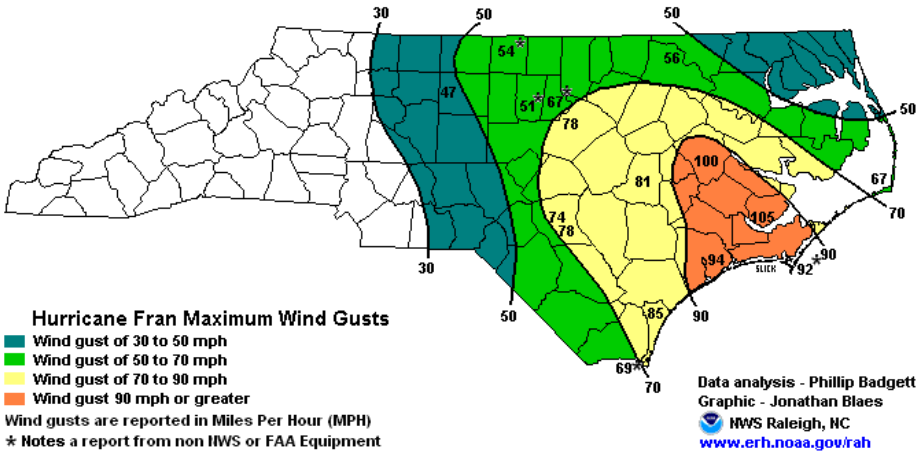

Figure 3.2.1c. Hurricane Fran maximum wind gusts. Source: NOAA.

Longer needles may make the trees more vulnerable to wind damage including loss of branches or blowdown as they would be exposed to more frictional drag. A similar theory was tested by Gresham *et al.* (1991) who hypothesized that longer longleaf pine needles would cause the tree to suffer more damage, but found that longleaf pine damage was markedly less than loblolly and pond pine due to its deeper root structure. Selection from repeated exposure to such high wind events may have led to a decrease in needle length within the North Carolina Coastal Plain longleaf pine gene pool, however this theory would warrant further testing. It is also possible that a combination of any or all of these hypotheses may work in concert to cause the geographic gradient in needle length.

3.2.2 Standardized DBH

Mean standardized DBH differed among all six sites, with sufficient evidence indicating the largest mean DHB stands were located on the Piedmont, followed by the Sandhills, and the thinnest trees located on the Coastal Plain. As with needle length, I propose several hypotheses that may indicate this pattern. Soil texture changes between

the three regions, from silt loams for Piedmont sites, to loamy sands for the Sandhills sites, to pure sands for the Coastal Plain sites (USDA, 2012). The silt-to-sand ratio may influence DBH for North Carolina longleaf pine, as nutrient availability and water retention is greater for the silt loams of the Piedmont and is progressively less for the loamy sands of the Sandhills, and sands of the Coastal Plain region. (Figure 3.2.1a). The best development of harvestable timber (defined by large DBH) exists where the subsoil contains considerable clay but is porous enough to allow for adequate percolation (Wahlenberg, 1946). In addition, sandy coastal sands produce fewer rings per inch than loamier soils further inland in southern Georgia (Lehrbas & Eldredge, 1941). Broader tree growth may be a disincentive for more coastal sites as the influence of strong wind-producing events such as tropical cyclones and hurricanes could easily topple trees with greater surface area. This theory also concurs with the findings of Gresham *et al.* (1991) where smaller diameter trees fared less damage than larger diameter of trees of differing species from hurricane Hugo.

3.2.3 Standardized tree height

Mean standardized tree height, as with needle length and DBH, differed among all six tracts. The mean tallest sites were on the Piedmont, followed by Sandhills, and the shortest mean height trees were located on the Coastal Plain. Mean standardized tree height for the Roberdo tract was significantly higher overall, differing from all but the Carvers tract. Following a similar pattern as with standardize DBH, mean standardized tree height is greatest for more inland sites and decreases towards the coast. Hypotheses that describe why North Carolina longleaf pine is taller further inland are similar to those

for needle length and DBH. First, soil texture indicating higher silt content may produce more favorable conditions for robust growth, as nutrient availability and water retention would be greater with an increase in silt content. As with needle length, a more competitive and closed broadleaf canopy may influence longleaf pine to grow taller to capture adequate sunlight for photosynthesis. For more coastal sites, taller trees may be more prone to wind-snap from high wind events, and with the lack of a competitive broadleaf canopy, a disincentive for height may exist.

3.2.4 All morphologic characteristics

The North Carolina longleaf pine stands within this study express a distinct geographic pattern in morphological characteristics. When grouping the three morphological characteristics and assessing them as a whole, I found that the sites farthest inland expressed more robust characteristics for they produced the longest mean needle lengths, largest mean DBH, and the greatest mean heights. Whether or not the observed pattern alludes to genetic differences in populations, which was not tested, the plasticity of North Carolina longleaf pine allow for distribution across varying ecotypes. A combination of soil type differences coupled with environmental pressures may select for stand morphological characteristics favorable to each region, leading to an inland to coastal gradient within North Carolina longleaf

CHAPTER IV

CLIMATE AND GROWTH RESPONSE

4.1 Results

4.1.1 PDSI

MXD was not significantly correlated with PDSI by site or region, therefore was excluded from further analysis. LW was significantly correlated with June–October PDSI for all six sites (Table 4.1.1a Figure 4.1.1a).

Table 4.1.1a. Correlations of latewood (LW) by location with average June–October PDSI.

		RTL LW	NTL LW	WWL LW	CCL LW	SLL LW	MRL LW
Piedmont PDSI	Pearson Correlation	.323**	.316**	.499**	.419**	0.183	0.027
	Sig. (2-tailed)	0.001	0.001	0	0	0.068	0.793
	N	100	100	100	100	100	100
Coastal PDSI	Pearson Correlation	.297**	.260**	.421**	.342**	.226*	.276**
	Sig. (2-tailed)	0.003	0.009	0	0	0.024	0.006
	N	100	100	100	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

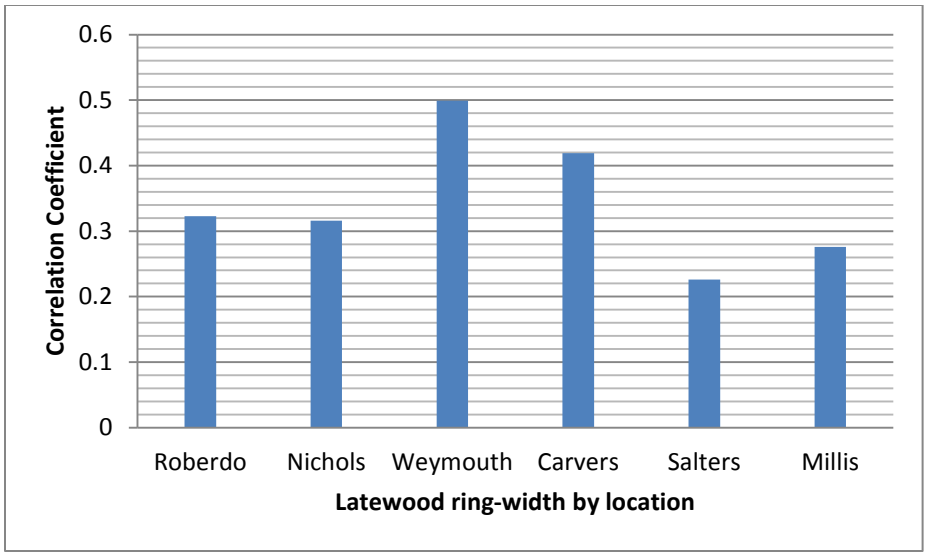

Figure 4.1.1a. Correlations of LW by location with average June–October PDSI.

The strongest correlation of the six sites was for Weymouth, and the weakest correlation was for Salters. When grouped by region, the Sandhills region had the strongest correlation with average June-October PDSI (r= 0.501) followed by the Piedmont region (r = 0.349) and the Coastal Plain region was not significantly correlated (Table 4.1.1b, Figure 4.1.1b).

Table 4.1.1b. Correlations of LW by region with average June-October PDSI.

		AVG LW-P	AVG LW-S	AVG LW-C
Piedmont PDSI	Pearson Correlation	.349**	.501**	-0.012
	Sig. (2-tailed)	0	0	0.908
	N	100	100	100
Coastal PDSI	Pearson Correlation	.283**	.416**	0.032
	Sig. (2-tailed)	0.004	0	0.749
	N	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

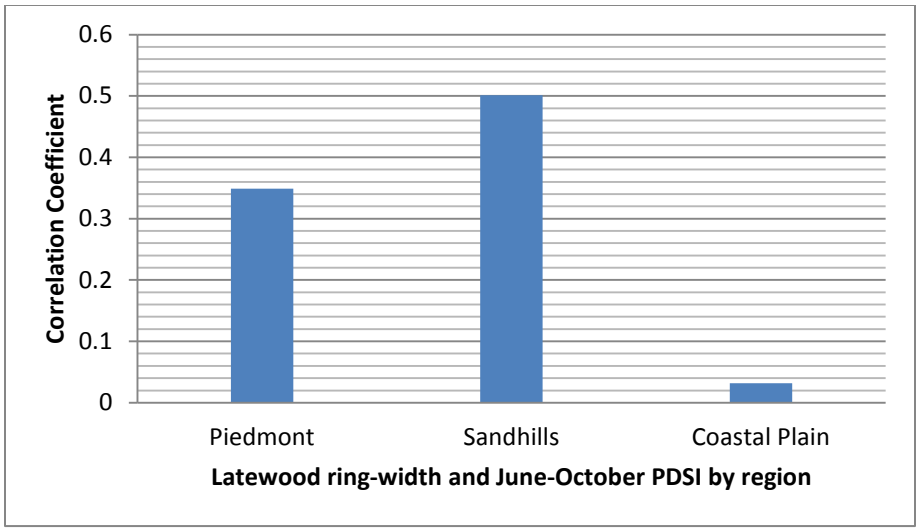

Figure 4.1.1b. Correlations of LW by region with average June–October PDSI.

Further, the correlation of the Piedmont region did not significantly differ from the correlation of the Sandhills region ($p > 0.05$).

TRW was significantly correlated with average June–October PDSI for all sites except Salters (Table 4.1.1c, Figure 4.1.1c).

Table 4.1.1c. Correlations of total ring width (TRW) by location with average June–October PDSI.

		RTL TRW	NTL TRW	WWL TRW	CCL TRW	SLL TRW	MRL TRW
Piedmont PDSI	Pearson Correlation	.329**	.223*	.389**	.329**	0.136	0.062
	Sig. (2-tailed)	0.001	0.026	0	0.001	0.179	0.541
	N	100	100	100	100	100	100
Coastal PDSI	Pearson Correlation	.260**	.208*	.315**	.243*	0.146	.265**
	Sig. (2-tailed)	0.009	0.037	0.001	0.015	0.147	0.008
	N	100	100	100	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed)

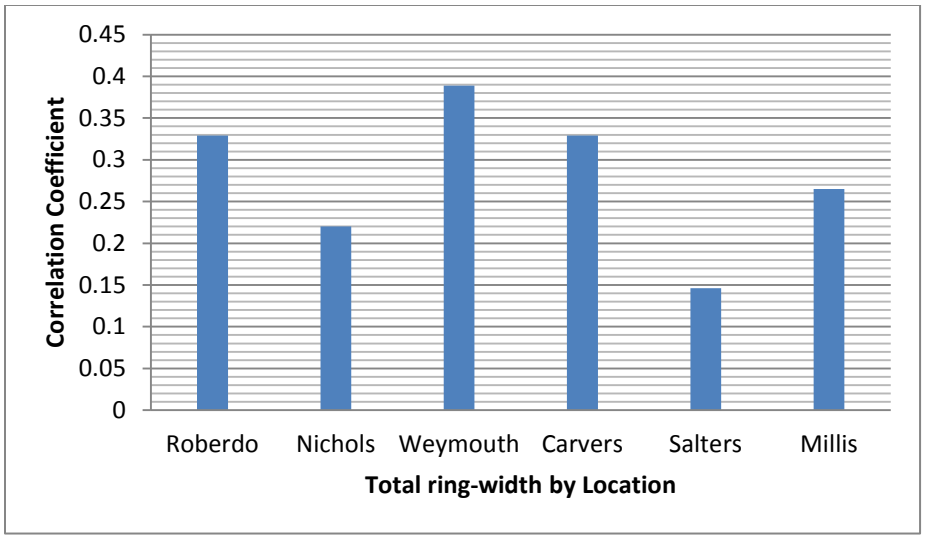

Figure 4.1.1c. Correlations of TRW by location with average June–October PDSI.

The strongest of the significant TRW correlations was for Weymouth (r = 0.389) and the weakest was for Nichols (r = 0.223). When grouped by region, all were significantly correlated with average June–October PDSI, with the strongest correlation belonging to the Sandhills region (r = 0.389) and the weakest to the Piedmont region (r = 0.297) (Table 4.1.1d, Figure 4.1.1d).

Table 4.1.1d. Correlations of TRW by region with average June-October PDSI.

		AVG TRW-P	AVG TRW-S	AVG TRW-C
Piedmont PDSI	Pearson Correlation	.297**	.389**	0.117
	Sig. (2-tailed)	0.003	0	0.246
	N	100	100	100
Coastal PDSI	Pearson Correlation	.253*	.299**	.315**
	Sig. (2-tailed)	0.011	0.002	0.001
	N	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

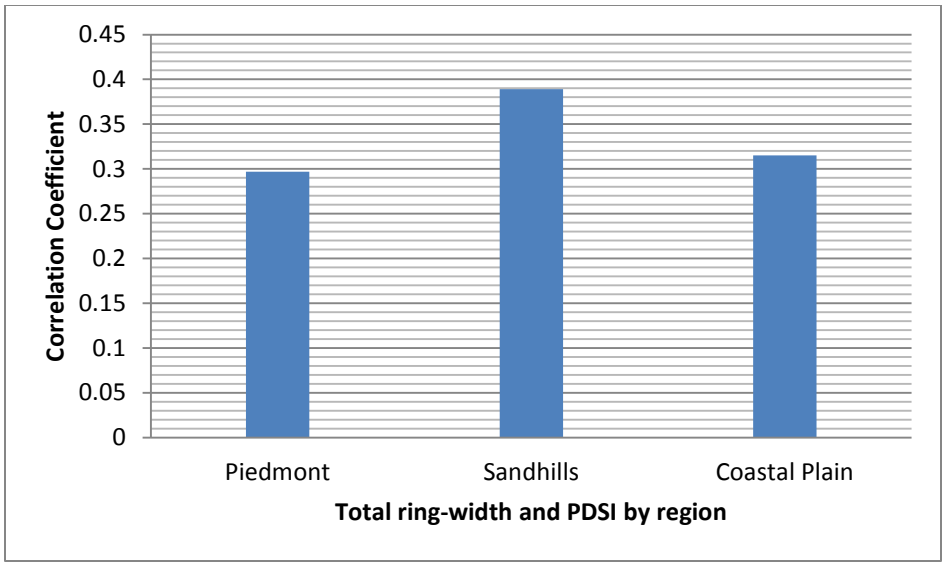

Figure 4.1.1d. Correlations of TRW by region with average June-October PDSI.

None of the regional correlations significantly differ from one another ($p > 0.05$).

4.1.2 Temperature

MXD was most negatively correlated with average Piedmont June–October temperatures for all sites except Weymouth (Table 4.1.2a, Figure 4.1.2a).

Table 4.1.2a. Correlations for average summer and June–October temperature and maximum latewood density (MXD) by location. P = Piedmont climate-division region C = Coastal Plain climate-division

		RTL MXD	NTL MXD	WWL MXD	CCL MXD	SLL MXD	MRL MXD
Summer-P	Pearson Correlation	-0.113	-0.101	0.025	-0.095	-0.055	-0.006
	Sig. (2-tailed)	0.263	0.317	0.804	0.345	0.59	0.951
	N	100	100	100	100	100	100
JJASO-P	Pearson Correlation	-.263**	-.267**	-0.169	-.279**	-.235*	-.199*
	Sig. (2-tailed)	0.008	0.007	0.092	0.005	0.019	0.047
	N	100	100	100	100	100	100

Summer-C	Pearson Correlation	0.134	0.118	0.164	0.137	.203*	0.19
	Sig. (2-tailed)	0.183	0.242	0.103	0.173	0.042	0.058
	N	100	100	100	100	100	100
JJASO-C	Pearson Correlation	-0.059	-0.074	-0.034	-0.084	-0.01	-0.018
	Sig. (2-tailed)	0.56	0.462	0.739	0.405	0.923	0.861
	N	100	100	100	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

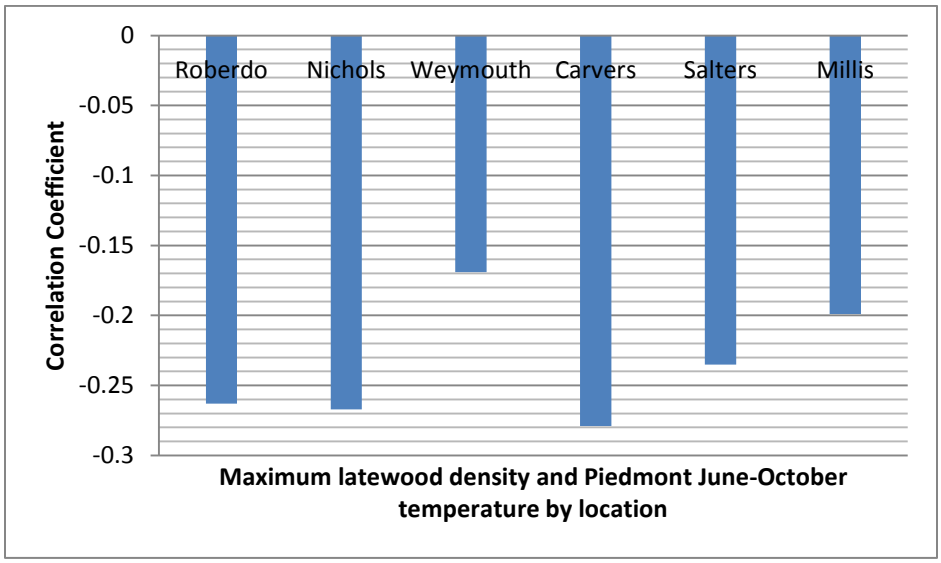

Figure 4.1.2a. Correlations for average Coastal June–October temperature and MXD by location.

When analyzed by region, MXD was more negatively correlated with average Piedmont June–October temperatures, with all sites expressing significant negative correlations (Table 4.1.2b, Figure 4.1.2b).

Table 4.2.1b. Correlations for average Piedmont and Coastal summer and June–October temperature and MXD by region. P = Piedmont climate-division region C = Coastal Plain climate-division

		AVG MXD_P	AVG MXD_S	AVG MXD_C
Summer-P	Pearson Correlation	-0.11	-0.047	-0.038
	Sig. (2-tailed)	0.274	0.645	0.71
	N	100	100	100
JJASO-P	Pearson Correlation	-.274**	-.245*	-.230*
	Sig. (2-tailed)	0.006	0.014	0.021
	N	100	100	100
Summer-C	Pearson Correlation	0.13	0.157	.206*
	Sig. (2-tailed)	0.197	0.119	0.039
	N	100	100	100
JJASO-C	Pearson Correlation	-0.069	-0.066	-0.013
	Sig. (2-tailed)	0.496	0.513	0.895
	N	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

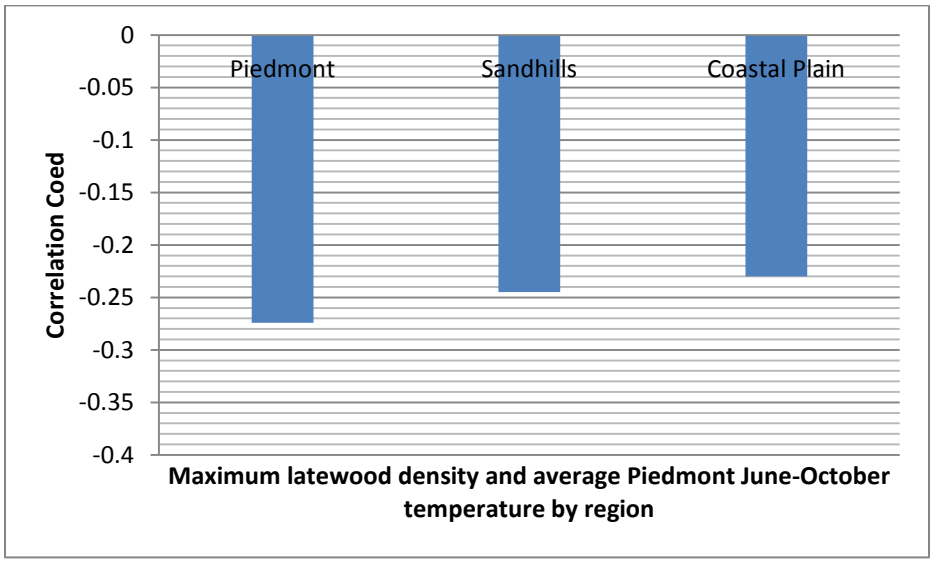

Figure 4.1.2b. Correlations for average Piedmont June–October temperature and MXD by region.

None of the significant regional MXD correlations significantly differ from one another ($p > 0.05$).

LW ring-width was most negatively correlated with average Piedmont summer temperature by location, and the Salters and Millis chronologies did not correlate with any temperature measure (Table 4.1.2c, Figure 4.1.2c).

Table 4.1.2c. Correlations for average summer and June–October temperature and LW by location.

		RTL LW	NTL LW	WWL LW	CCL LW	SLL LW	MRL LW
Summer-P	Pearson Correlation	-.206*	-.205*	-.261**	-.292**	-0.067	-0.13
	Sig. (2-tailed)	0.04	0.041	0.009	0.003	0.505	0.198
	N	100	100	100	100	100	100
JJASO-P	Pearson Correlation	-0.179	-0.168	-.274**	-.298**	-0.065	0.002
	Sig. (2-tailed)	0.075	0.095	0.006	0.003	0.522	0.985
	N	100	100	100	100	100	100
Summer-C	Pearson Correlation	-0.141	-0.153	-0.19	-.223*	-0.089	-0.118
	Sig. (2-tailed)	0.162	0.129	0.058	0.026	0.379	0.242
	N	100	100	100	100	100	100
JJASO-C	Pearson Correlation	-0.134	-0.131	-.219*	-.260**	-0.087	-0.035
	Sig. (2-tailed)	0.185	0.194	0.029	0.009	0.392	0.73
	N	100	100	100	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

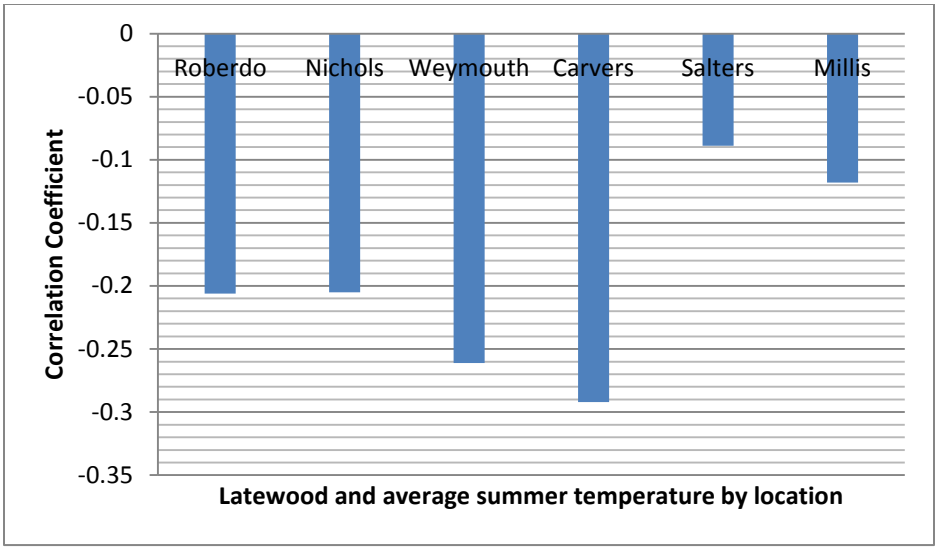

Figure 4.1.2c. Correlations for average summer temperature and LW by location.

When analyzed by region, the strongest negative correlations were for the Sandhills region for both average Piedmont and Coastal summer and average Piedmont and Coastal June–October temperatures (Table 4.1.2d, Figure 4.1.2d). The Piedmont region was only negatively correlated with average summer Piedmont temperature whereas no correlation existed for the Coastal Plain region.

Table 4.1.2d. Correlations for average summer and June–October temperature and LW by region.

		AVG LW_P	AVG LW_S	AVG LW_C
Summer-P	Pearson Correlation	-.223*	-.303**	-0.128
	Sig. (2-tailed)	0.025	0.002	0.206
	N	100	100	100
JJASO-P	Pearson Correlation	-0.187	-.313**	-0.033
	Sig. (2-tailed)	0.062	0.001	0.741
	N	100	100	100
Summer-C	Pearson Correlation	-0.161	-.227*	-0.131
	Sig. (2-tailed)	0.109	0.023	0.194

	N	100	100	100
JJASO-C	Pearson Correlation	-0.143	-.263**	-0.071
	Sig. (2-tailed)	0.155	0.008	0.482
	N	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed)

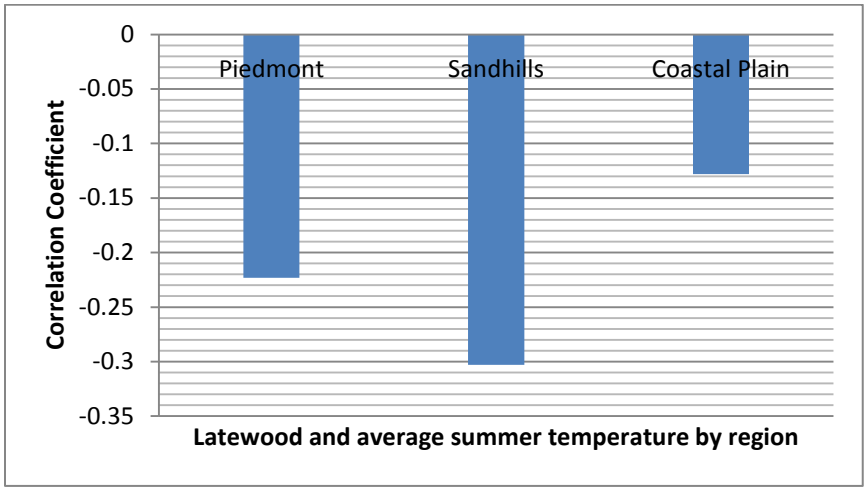

Figure 4.1.2d. Correlations for average summer temperature and LW by region. None of the significant regional LW correlations significantly differed from one another ($p > 0.05$).

TRW was negatively correlated with average Piedmont summer temperatures for all locations except Salters and Millis, which expressed no significant correlation with temperature (Table 4.1.2e, Figure 4.1.2e)

Table 4.1.2e. Correlations for average summer and June–October temperature and TRW by location.

		RTL TRW	NTL TRW	WWL TRW	CCL TRW	SLL TRW	MRL TRW
Summer-P	Pearson Correlation	-.206*	-.213*	-.205*	-.263**	-0.055	-0.168
	Sig. (2-tailed)	0.04	0.033	0.041	0.008	0.585	0.095
	N	100	100	100	100	100	100

JJASO-P	Pearson Correlation	-0.179	-0.177	-.197*	-.263**	-0.027	-0.034
	Sig. (2-tailed)	0.075	0.079	0.049	0.008	0.789	0.738
	N	100	100	100	100	100	100
Summer-C	Pearson Correlation	-0.141	-0.172	-0.175	-.215*	-0.072	-0.137
	Sig. (2-tailed)	0.162	0.088	0.081	0.032	0.478	0.174
	N	100	100	100	100	100	100
JJASO-C	Pearson Correlation	-0.134	-0.162	-0.182	-.245*	-0.049	-0.053
	Sig. (2-tailed)	0.185	0.108	0.07	0.014	0.629	0.6
	N	100	100	100	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

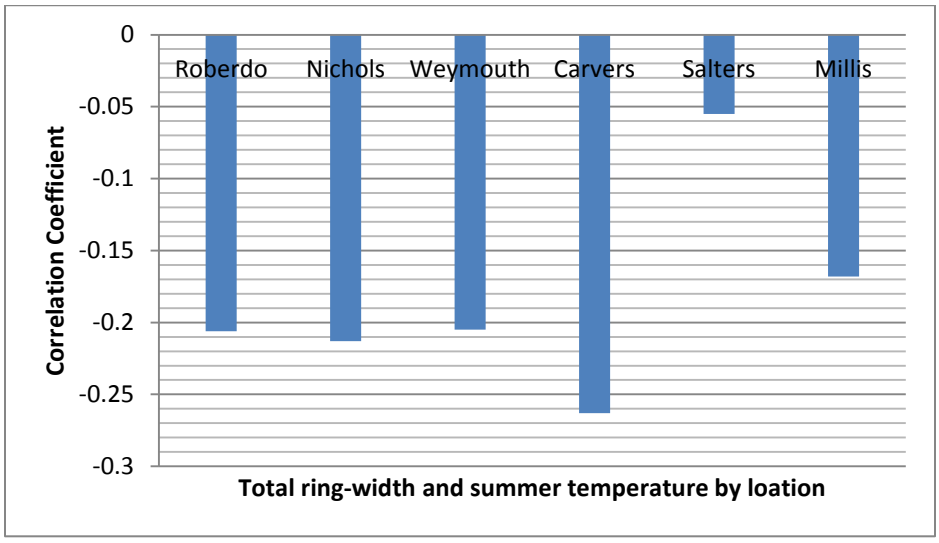

Figure 4.1.2e. Correlations for average Piedmont summer temperature and TRW by location.

When analyzed by region, the strongest negative correlations were for the Sandhills region for average summer temperatures (Table 4.1.2f, Figure 4.1.2f). Coastal Plain sites exhibited no significant correlations with temperature.

Table 4.1.2f. Correlations for average summer and June–October temperature and TRW by region.

		AVG TRW_P	AVG TRW_S	AVG TRW_C
Summer-P	Pearson Correlation	-.227*	-.259**	-0.139
	Sig. (2-tailed)	0.023	0.009	0.167
	N	100	100	100
JJASO-P	Pearson Correlation	-0.193	-.255*	-0.037
	Sig. (2-tailed)	0.055	0.01	0.715
	N	100	100	100
Summer-C	Pearson Correlation	-0.17	-.216*	-0.128
	Sig. (2-tailed)	0.091	0.031	0.203
	N	100	100	100
JJASO-C	Pearson Correlation	-0.161	-.237*	-0.061
	Sig. (2-tailed)	0.11	0.018	0.543
	N	100	100	100

** Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

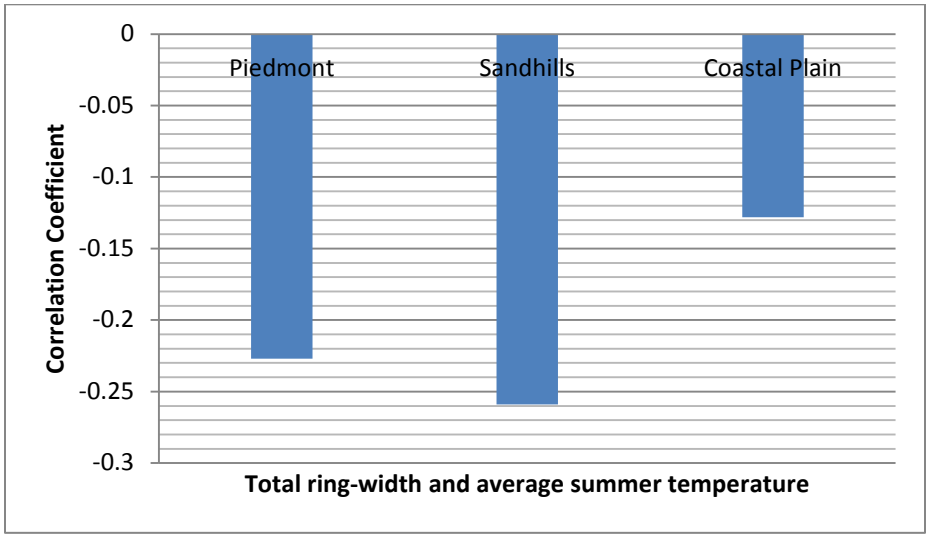

Figure 4.1.2f. Correlations for average summer temperature and TRW by region.

None of the significant regional TRW correlations significantly differed from one another ($p > 0.05$).

4.1.3 Precipitation

MXD did not significantly correlate with any precipitation data, therefore was omitted from further analysis. Moderate positive correlations were found for average Piedmont June–October precipitation and LW for all sites except Salters and Millis(Table 4.1.3a, Figure 4.1.3a).

Table 4.1.3a. Correlations for average summer and June–October precipitation and LW by location.

		RTL LW	NTL LW	WWL LW	CCL LW	SLL LW	MRL LW
Summer-P	Pearson Correlation	.256*	.407**	.410**	.385**	0.109	-0.113
	Sig. (2-tailed)	0.01	0	0	0	0.28	0.261
	N	100	100	100	100	100	100
JJASO-P	Pearson Correlation	.317**	.442**	.424**	.406**	0.182	-0.065
	Sig. (2-tailed)	0.001	0	0	0	0.071	0.518
	N	100	100	100	100	100	100
Summer-C	Pearson Correlation	0.035	0.158	.207*	.249*	0.191	0.022
	Sig. (2-tailed)	0.726	0.116	0.039	0.012	0.057	0.827
	N	100	100	100	100	100	100
JJASO-C	Pearson Correlation	0.17	.264**	.337**	.316**	.283**	0.157
	Sig. (2-tailed)	0.091	0.008	0.001	0.001	0.004	0.118
	N	100	100	100	100	100	100

** Correlation is significant at the 0.01 level (2tailed).

* Correlation is significant at the 0.05 level (2-tailed).

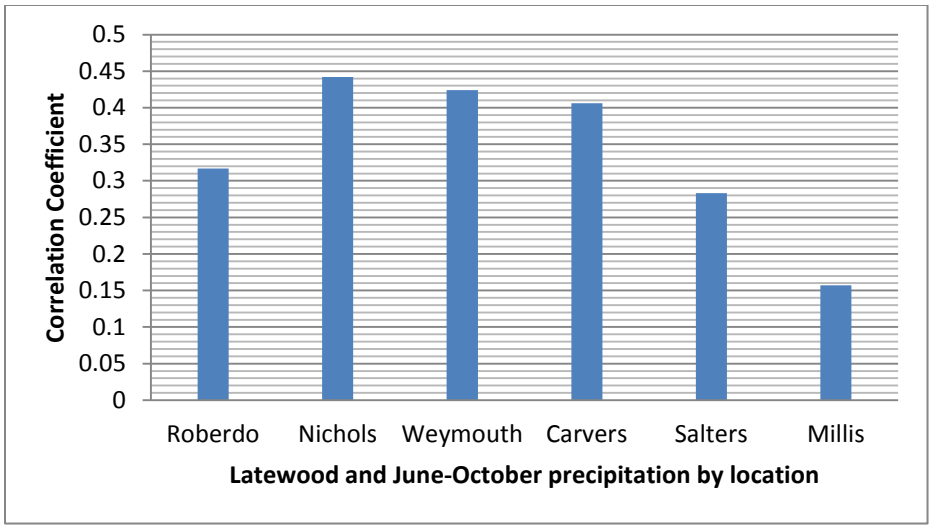

Figure 4.1.3a. Latewood and average June–October precipitation correlations by location.

The strongest correlations were for Nichols (r = 0.442) and the weakest were for Millis (r = 0.157). Subtle variations exist between the five significant correlations as all locations expressed a similar response to average June–October precipitation. When grouped by region, all regions correlated positively with June–October precipitation (Table 4.1.3b, Figure 4.1.3b).

Table 4.1.3b. Correlations for average summer and June-October precipitation and LW by region.

		AVG LW_P	AVG LW_S	AVG LW_C
Summer-P	Pearson Correlation	.379**	.434**	-0.021
	Sig. (2-tailed)	0	0	0.834
	N	100	100	100
JJASO-P	Pearson Correlation	.428**	.454**	0.052
	Sig. (2-tailed)	0	0	0.61
	N	100	100	100
Summer-C	Pearson	0.121	.251*	0.118

	Correlation			
	Sig. (2-tailed)	0.232	0.012	0.24
	N	100	100	100
JJASO-C	Pearson Correlation	.248*	.357**	.263**
	Sig. (2-tailed)	0.013	0	0.008
	N	100	100	100

** Correlation is significant at the 0.01 level (2tailed).

* Correlation is significant at the 0.05 level (2-tailed).

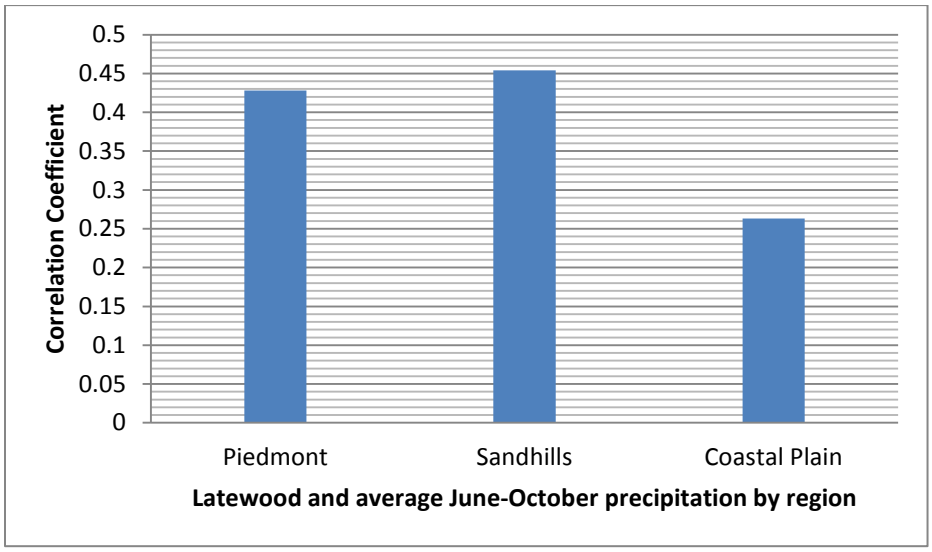

Figure 4.1.3b. Latewood and average June–October precipitation correlations by region

Correlations between the Piedmont and Sandhills regions did not significantly differ ($p > 0.05$), however the Sandhills region was significantly greater than Coastal Plain region ($p = 0.0624$) when $\alpha = 0.1$ level.

TRW exhibited the strongest positive correlation with average June–October precipitation for all sites except Salters and Millis that did not correlate significantly (Table 4.1.3c, Figure 4.1.3c)

Table 4.1.3c. Correlations for average summer and June–October precipitation and TRW by location.

		RTL TRW	NTL TRW	WWL TRW	CCL TRW	SLL TRW	MRL TRW
Summer-P	Pearson Correlation	.256*	.242*	.233*	.257**	0.001	-0.128
	Sig. (2-tailed)	0.01	0.015	0.02	0.01	0.994	0.205
	N	100	100	100	100	100	100
JJASO-P	Pearson Correlation	.317**	.295**	.288**	.289**	0.043	-0.065
	Sig. (2-tailed)	0.001	0.003	0.004	0.004	0.674	0.518
	N	100	100	100	100	100	100
Summer-C	Pearson Correlation	0.035	0.01	0.032	0.058	0.015	-0.035
	Sig. (2-tailed)	0.726	0.922	0.754	0.567	0.886	0.726
	N	100	100	100	100	100	100
JJASO-C	Pearson Correlation	0.17	0.104	0.171	0.137	0.064	0.117
	Sig. (2-tailed)	0.091	0.304	0.089	0.175	0.524	0.248
	N	100	100	100	100	100	100

** Correlation is significant at the 0.01 level (2tailed).
* Correlation is significant at the 0.05 level (2-tailed).

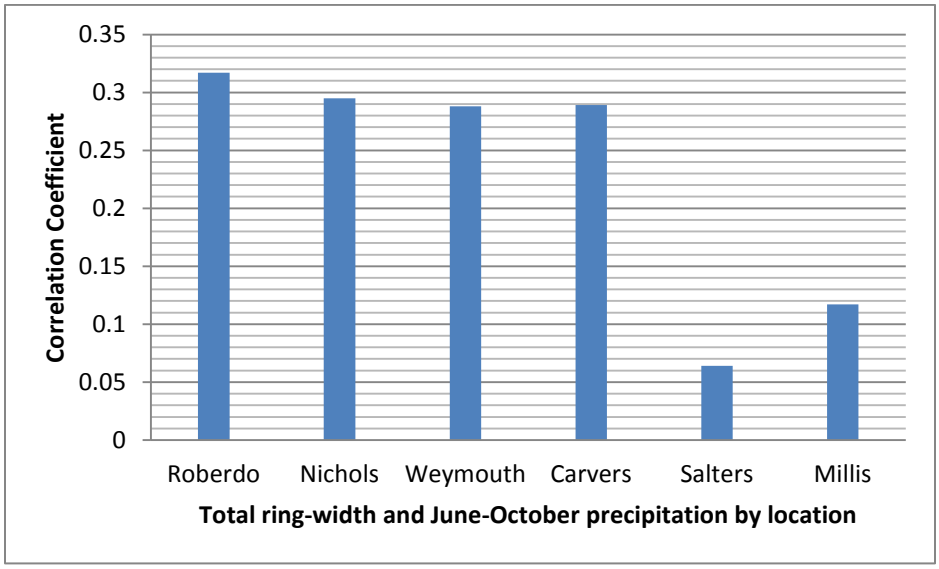

Figure 4.1.3c. TRW and average June–October precipitation correlations by location

When grouped by region, only the Piedmont and Sandhills exhibited significant positive correlations (Table 4.1.3d, Figure 4.1.3d).

Table 4.1.3d. Correlations for average summer and June–October precipitation and TRW by region.

		AVG TRW_P	AVG TRW_S	AVG TRW_C
Summer-P	Pearson Correlation	.269**	.271**	-0.082
	Sig. (2-tailed)	0.007	0.006	0.415
	N	100	100	100
JJASO-P	Pearson Correlation	.331**	.318**	-0.019
	Sig. (2-tailed)	0.001	0.001	0.854
	N	100	100	100
Summer-C	Pearson Correlation	0.024	0.05	-0.015
	Sig. (2-tailed)	0.814	0.62	0.883
	N	100	100	100
JJASO-C	Pearson Correlation	0.146	0.169	0.111
	Sig. (2-tailed)	0.147	0.094	0.27
	N	100	100	100

** Correlation is significant at the 0.01 level (2tailed).

* Correlation is significant at the 0.05 level (2-tailed).

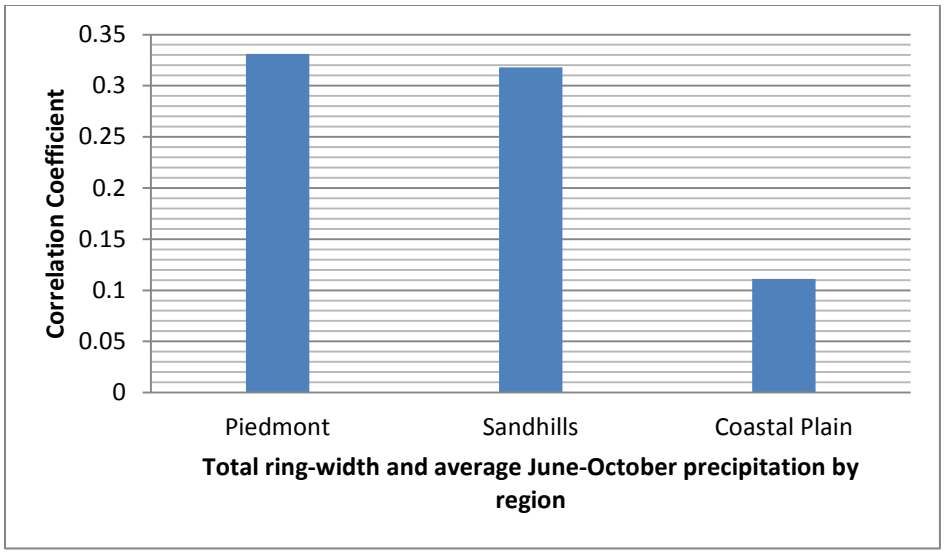

Figure 4.1.3d. TRW and average Piedmont June–October precipitation correlations by region.

As with LW, TRW correlations between the Piedmont and Sandhills regions did not significantly differ from one another ($p > 0.05$).

4.1.4 Lag relationships

When average June–October PDSI values were lagged by one year, the Coastal Plain region exhibited a near significant ($p < 0.088$) correlation, whereas the Piedmont and Sandhills regions did not (Table 4.1.4a, Figure 4.1.4a).

Table 4.1.4a. Correlations of previous year's average June–October PDSI and LW by region.

		AVG LW_P	AVG LW_S	AVG LW_C
PREV_JJASO	Pearson Correlation	0.037	-0.121	0.171
	Sig. (2-tailed)	0.718	0.229	0.088
	N	100	100	100

** Correlation is significant at the 0.01 level (2tailed).
* Correlation is significant at the 0.05 level (2-tailed).

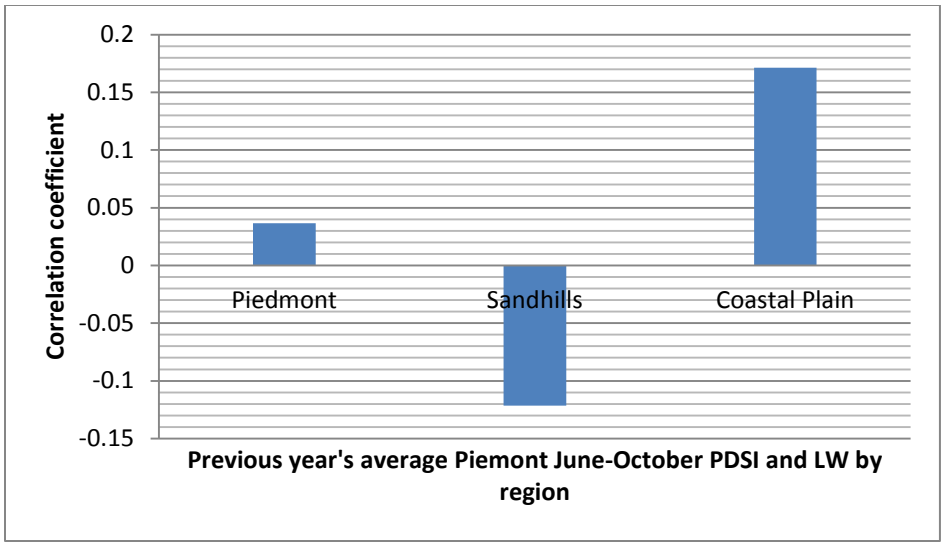

Figure 4.1.4a. LW and previous year's average Piedmont June–October PDSI correlations by region.

When temperature values were lagged one year, only Coastal Plain LW exhibited a significant positive correlation with average Piedmont June–October precipitation for (Table 4.1.4b, Figure 4.1.4b).

Table 4.1.4b. Correlations of previous year's average Piedmont June–October precipitation and LW by region.

		AVG LW_P	AVG LW_S	AVG LW_C
PRE_JJASO_P	Pearson Correlation	-0.06	-0.085	.223*
	Sig. (2-tailed)	0.555	0.401	0.026
	N	100	100	100

** Correlation is significant at the 0.01 level (2tailed).

* Correlation is significant at the 0.05 level (2-tailed).

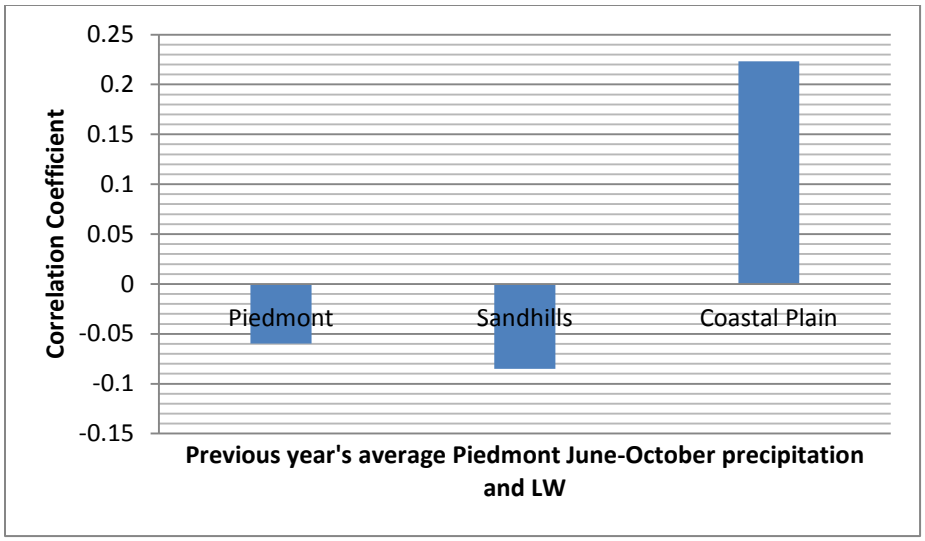

Figure 4.1.4b. LW and previous year's average Piedmont June–October precipitation correlations by region.

When temperature values were lagged by one year, MXD for all regions exhibited a significant negative correlation with average Piedmont June-October temperature.

Table 4.1.4c. Correlations of previous year's average Piedmont June–October temperature and MXD by region.

		AVG MXD_P	AVG MXD_S	AVG MXD_C
Prev_JJOSO-_TEMP	Pearson Correlation	-.332**	-.283**	-.264**
	Sig. (2-tailed)	0.001	0.004	0.008
	N	100	100	100

** Correlation is significant at the 0.01 level (2tailed).

* Correlation is significant at the 0.05 level (2-tailed).

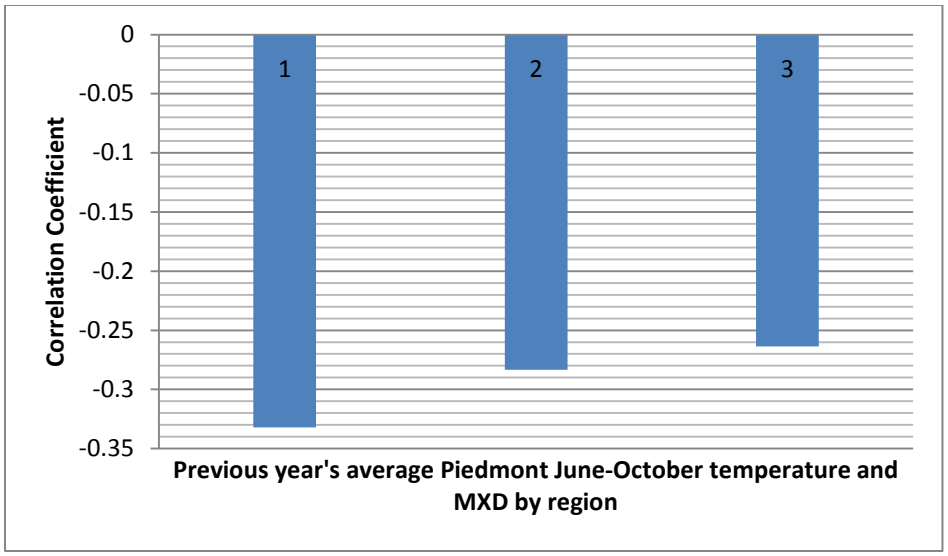

Figure 4.1.4c. MXD and previous year's average Piedmont June–October temperature correlations by region.

None of the lagged correlations significantly differed from one another ($p > 0.05$).

4.1.5 MXD divergence

MXD forms two distinct groups from the mid-1950s to present. The higher-density group includes the two Piedmont tracts and Carvers tract, and the lower-density group includes the two Coastal Plain tracts and Weymouth tract (Figure 4.1.5a).

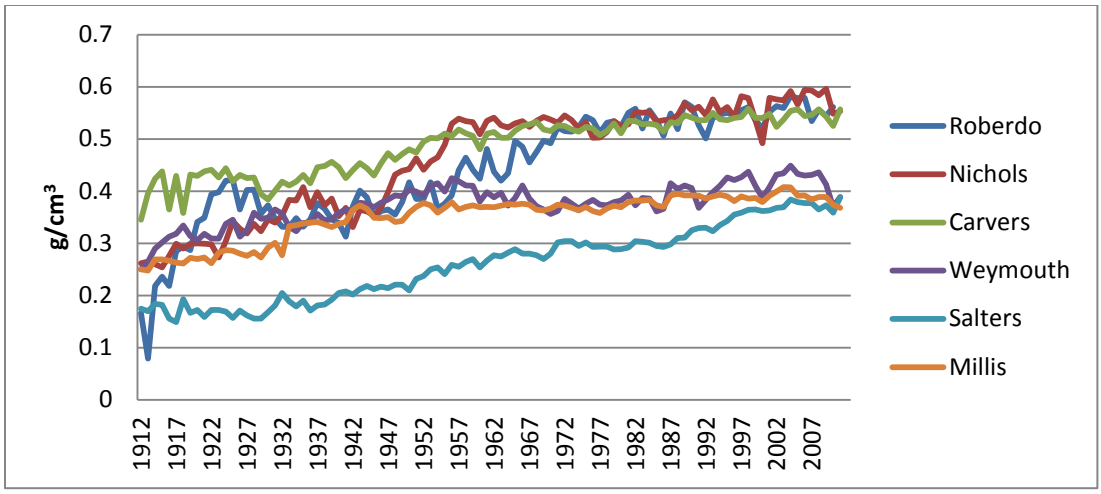

Figure 4.1.5a. Maximum latewood density diverging into two distinct density groups.

I tested if within the last 40 years of the chronologies (1972–1911) MXD significantly differs by both locational and zonal grouping. ANOVA analysis was used to test if MXD differed by location and an independent-samples t-test was used for the group testing. ANOVA results indicate there is a difference in means between all six locations ($p < 0.001$, Table 4.1.5a).

Table 4.1.5a. ANOVA results for a difference in means between locations.

ANOVA: MXD by location	DF	Mean Sq	Sum Sq	F value	*p* value
Location	5	1.876	0.375	695.1	<2e-16 ***
Residuals	234	0.126	0.001		

** Correlation is significant at the 0.01 level (2tailed).
* Correlation is significant at the 0.05 level (2-tailed).

The three high-density zone tracts do not differ when $\alpha = 0.01$, and the only non-different comparison of the low-density zone was between Millis and Weymouth ($p =$

0.0145, Table 4.1.5b). All other locational comparisons significantly differed (p > 0.001).

Table 4.1.5b. Non-significantly different (p > 0.001) Tukey-Kramer pairwise comparisons by location.

Comparison	Estimate	Standard Error	t value	p value
Nichols - Roberdo	0.008250	0.005191	1.589	0.6066
Carvers - Roberdo	-0.008300	0.005191	-1.599	0.6002
Carvers - Nichols	-0.016550	0.005191	-3.188	0.0200 *
Millis - Weymouth	-0.017075	0.005191	-3.289	0.0145 *

** Correlation is significant at the 0.01 level (2tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Using the Welch two sample t-test, I found that the two groups significantly differed from one another (Table 4.1.5c)

Table 4.1.5c. Welch t-test results for a difference in means between the high and low MXD groups.

t value	DF	p value	95% Confidence interval	Means
42.558	188.87	< 2.2e-16	0.16367–0.1796	high = 0.543 low = 0.371

Box plots for locational and group MXD display the differences in means between locations and the two groups (Figures 4.1.5b, c).

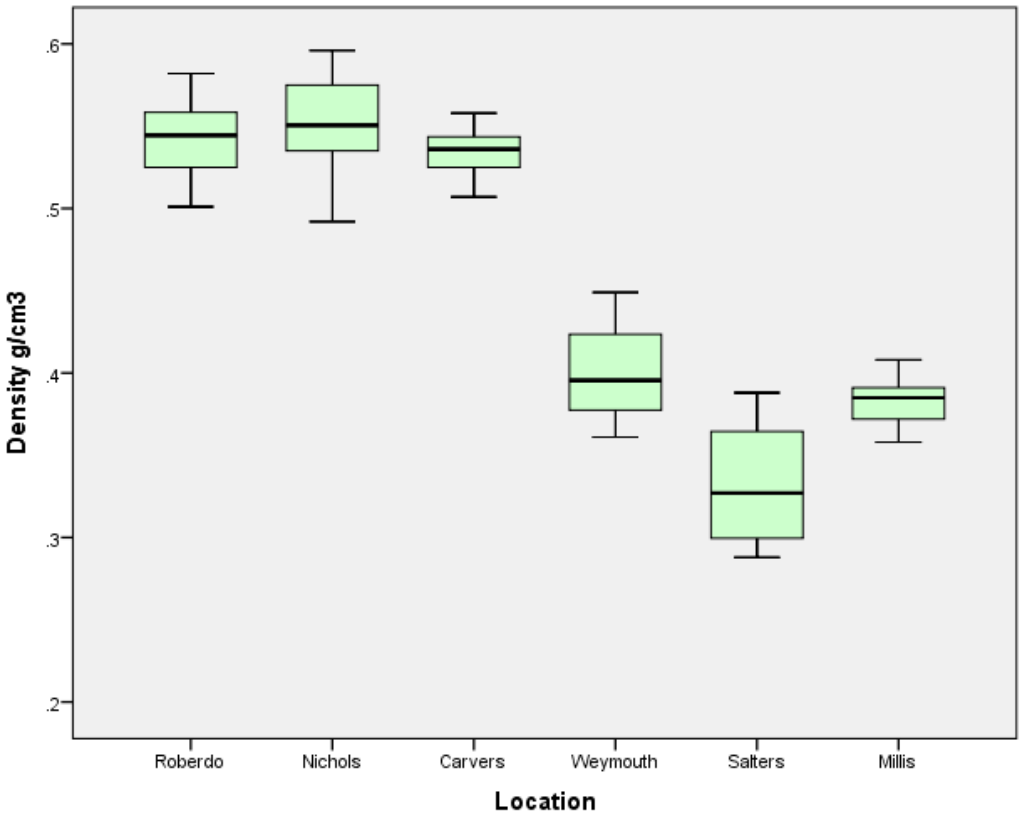

Figure 4.1.4b. Boxplot of MXD by location. Potential influential-points and outliers are identified by either a circle or star.

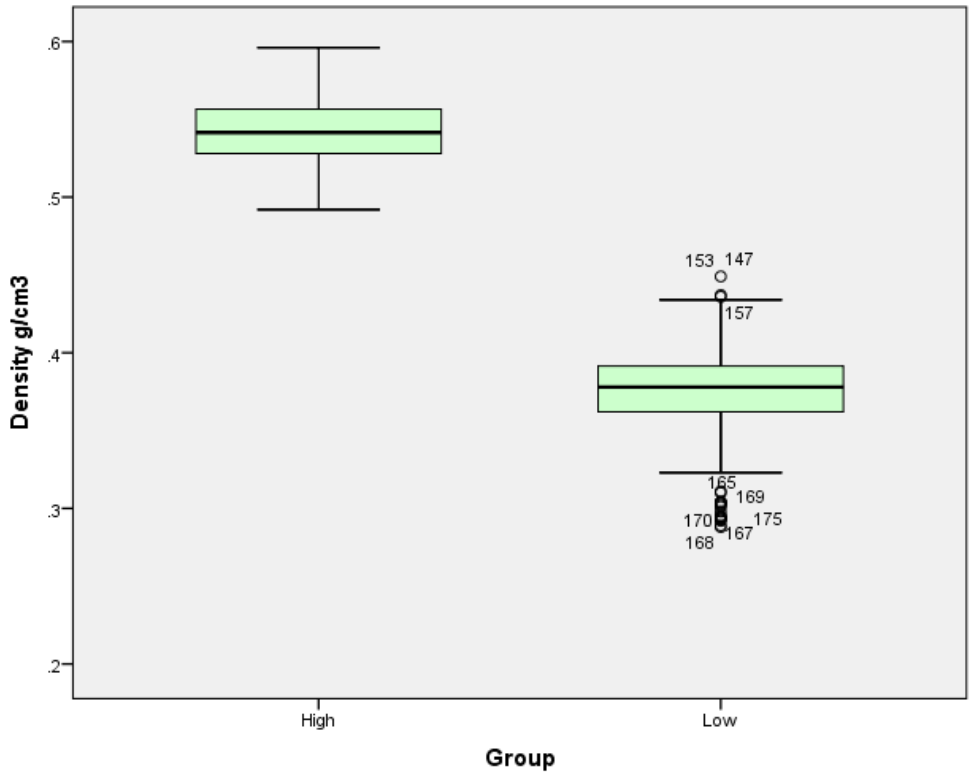

Figure 4.1.5c. Boxplot of MXD by group. Potential influential-points and outliers are identified by either a circle or star.

4.1.6 Mean sensitivity and interseries correlation analysis

Four descriptive statistics explain the quality of each sites' chronology for TRW, LW and MXD. These include sample size (*i*), interseries correlation (IC), which measures the strength of the common signal of the chronology and is a measure of the chronology reliability (NOAA, 2008), mean sensitivity (MS), which is the relative change in ring-width from one year to the next, and the expressed population signal (EPS), which is a measure for a chronology's sample depth through time (Table 4.1.6a). An EPS value > 0.85 is considered robust (Wigley *et al.*, 1984). I

was unable to obtain EPS values for MXD as EPS values are provided post detrending, which was unnecessary with MXD.

Table 4.1.6a. Descriptive statistics for IC, MS, and EPS. N/A = not available.

Location	Measurement	n	IC	MS	EPS $\geq$ 0.85
Roberdo	TRW	31	0.538	0.299	1920
	LW	31	0.514	0.406	1929
	MXD	31	0.124	0.164	N/A
Nichols	TRW	30	0.565	0.32	1838
	LW	30	0.509	0.495	1866
	MXD	30	0.205	0.177	N/A
Weymouth	TRW	27	0.537	0.290	1921
	LW	27	0.447	0.487	1929
	MXD	27	0.167	0.155	N/A
Carvers	TRW	28	0.527	0.325	1900
	LW	28	0.572	0.519	1893
	MXD	28	0.124	0.114	N/A
Salters	TRW	25	0.48	0.278	1936
	LW	25	0.329	0.488	1944
	MXD	25	0.127	0.158	N/A
Millis	TRW	32	0.432	0.373	1881

	LW	32	0.375	0.631	1871
	MXD	32	0.166	0.104	N/A

TRW IC was strongest for Nichols and is weakest for Millis. LW IC was strongest for Carvers and weakest for Salters. All MXD IC were low, with the strongest for Nichols and the weakest were equal for Carvers and Roberdo. TRW IC was > LW IC for all sites except carvers. MS was consistently higher for LW than for TRW and MXD. TRW MS was highest for Millis and lowest for Salters. LW MS was highest for Salters and lowest for Roberdo. MXD MS was highest for Nichols and lowest for Millis. TRW EPS values > 0.85 were achieved for 1921 to present for all sites, and the furthest dated to AD 1838 for Nichols. LW EPS values > 0.85 were achieved for 1944 to present for all sites, the furthest dated to AD 1866 for Nichols.

ANOVA analysis was conducted to test if a difference in means exists for TRW IC and MS between tracts and by region. A significant difference in means for IC existed by location ($p < 0.001$, Table 4.1.6b).

Table 4.1.6b. ANOVA results for TRW IC by location.

ANOVA: TRW IC by location	DF	Sum of squares	Mean Square	F value	*p* value
Fitted	5	0.4787	0.09573	11.56	1.31e-09 ***
Residuals	168	1.3909	0.00828		

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

All Significant TRW IC Tukey-Kramer pairwise comparisons ($p < 0.1$) by location are summarized in Table 4.1.6c.

Table 4.1.6c. Significant ($p < 0.1$) TRW IC pairwise comparisons by location.

TRW IC pairwise comparisons by location				
Comparison	Estimate	Standard Error	t value	*p* value
Millis - Roberdo	-0.109062	0.022747	-4.795	<0.001 ***
Salters - Nichols	-0.099253	0.024640	-4.028	0.00117 **
Millis - Nichols	-0.163158	0.023123	-7.056	<0.001 ***
Millis - Carvers	-0.112125	0.023546	-4.762	<0.001 ***
Millis - Weymouth	-0.116255	0.023777	-4.889	<0.001 ***
Millis - Salters	-0.063905	0.024287	-2.631	0.09525
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1				

TRW IC also expressed a difference in means when tested by region ($p < 0.001$, Table 4.1.6d)

Table 4.1.6d. ANOVA results for TRW IC by region.

ANOVA: TRW IC by region	DF	Sum of squares	Mean Square	F value	*p* value
Fitted	2	0.3758	0.18790	21.51	4.65e-09 ***
Residuals	171	1.4937	0.00874		

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

All significant TRW IC Tukey-Kramer pairwise comparisons ($p < 0.1$) by region are summarized in Table 4.1.6e

Table 4.1.6e. Significant ($p < 0.1$) TRW IC pairwise comparisons by region.

TRW IC pairwise comparisons by location				
Comparison	Estimate	Standard Error	t value	*p* value
Piedmont - Coastal Plain	0.10721	0.01715	6.251	<1e-04 ***
Sandhills - Coastal Plain	0 0.08612	0.01767	4.875	<1e-04 ***
Sandhills - Piedmont	-0.02109	0.01731	-1.218	0.444
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1				

ANOVA analysis expressed a significant difference in means for TRW MS among the six locations ($p < 0.001$, Table 4.1.6f)

Table 4.1.6f. ANOVA results for TRW MS by location.

ANOVA: TRW MS by location	DF	Sum of squares	Mean Square	F value	*p* value
Fitted	5	0.7199	0.14397	50.16	<2e-16 ***
Residuals	168	0.4822	0.00287		

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

All significant ($p < 0.1$) TRW MS Tukey-Kramer pairwise comparisons by location are summarized in Table 4.1.6g.

Table 4.1.6g. Significant ($p < 0.1$) TRW MS pairwise comparisons by location.

TRW MS pairwise comparisons by location				
Comparison	Estimate	Standard Error	t value	*p* value
Millis - Carvers	0.05355	0.01386	3.863	0.00229 **
Nichols - Carvers	-0.15384	0.01408	-10.928	< 0.001 ***

Salters - Carvers	-0.163158	0.01474	-3.193	0.02049 *
Nichols - Millis	-0.20739	0.01362	-15.232	< 0.001 ***
Roberdo - Millis	-0.07244	0.01339	-5.408	< 0.001 ***
Salters - Millis	-0.10062	0.01430	-7.036	< 0.001 ***
Weymouth - Millis	-0.08985	0.01400	-6.418	< 0.001 ***
Roberdo - Nichols	0.13495	0.01362	9.912	< 0.001 ***
Salters - Nichols	0.10677	0.01451	7.359	< 0.001 ***
Weymouth - Nichols	0.11754	0.01421	8.271	< 0.001 ***
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1				

When grouped by region, TRW MS expressed a significant difference in means ($p <$ 0.001, Table 4.1.6h)

Table 4.1.6h. ANOVA results for TRW MS by region.

ANOVA: TRW MS by region	DF	Sum of squares	Mean Square	F value	*p* value
Fitted	2	0.2776	0.13882	25.68	1.77e-10 ***
Residuals	171	0.9244	0.00541		

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

All significant ($p < 0.1$) TRW MS Tukey-Kramer pairwise comparisons by region are summarized in Table 4.1.6i.

Table 4.1.6i. Significant ($p < 0.1$) TRW MS pairwise comparisons by region.

TRW MS pairwise comparisons by location				
Comparison	Estimate	Standard Error	t value	*p* value
Piedmont - Coastal Plain	-0.09360	0.01349	-6.938	<1e-04 ***
Sandhills - Coastal Plain	-0.02724	0.01390	-1.960	0.125

Sandhills - Piedmont	0.06637	0.01362	4.873	<1e-04 ***
Significance codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1				

4.2 Discussion

Few studies have tested climate/tree-ring growth relationships along a species-range gradient and this study is the first for longleaf pine tracts in North Carolina. Adequate sample depth per site assures the assumptions of normality and constant variance were met; however, bias taken during sampling for old and healthy trees failed the assumption for independent and random observations. Thus, results pertain to the six studied longleaf pine tracts in North Carolina, and assumptions about longleaf pine throughout their geographic range would be inappropriate.

4.2.1 PDSI

Average June–October Coastal PDSI expressed significant positive correlations with LW for all six locations. When grouped by region, the Sandhills region had the strongest correlation with average Piedmont June–October PDSI, followed by the Piedmont region, and the Coastal Plain region did not express a significant correlation. When lagged one year, the Coastal Plain LW was positively correlated with average June–October Piedmont PDSI. TRW correlations were weaker than LW correlations, but positive correlations were associated with all locations except Salters. Additionally, when grouped by region all expressed significant positive correlations but no region significantly differ from one another. These results confirm with the work of Henderson and Grissino-Mayer (2008) as the

strongest tree-ring climate relationships were for PDSI, and that this relationship was strongest for July–November and for LW rather than TRW. No distinct west–east gradient existed for PDSI growth response that mirrors the results of the morphological characteristic analysis.

4.2.2 Temperature

Tree-ring growth was negatively correlated for all growth measures, and all growth measures expressed correlations of similar strength. These results are similar to Henderson and Grissino-Mayer (2008) who found weak negative correlations between average summer temperature and growth measures. I chose to use MXD with average temperature as no study has used MXD with longleaf pine. Further, studies using various tree species have all found positive correlations between MXD and temperature (D'Arrigo *et al.*, 2000, Davi *et al.*, 2003, Beck *et al.*, 2013). The opposite was true for longleaf pine, as I found consistent negative correlations between average temperature and MXD. Further, MXD was the only measurement where all regions significantly correlated to average temperature, whereas with LW and TRW only the Piedmont and Sandhills regions were negatively correlated. No regional correlations significantly differed from one another.

4.2.3 Precipitation

Both LW and TRW were positively correlated with average precipitation, whereas MXD did not significantly correlate with any precipitation measure. Average June–October precipitation correlations were higher for LW than for TRW. The Sandhills region expressed the strongest correlation for June–October precipitation

for LW, and the Piedmont region had the strongest correlation for average June–October TRW. Only one regional correlation significantly differed from one another, which was between Sandhills and Coastal Plain for average June–October average precipitation and LW, and Coastal Plain sites only expressed a positive correlation with LW and average June–October precipitation. No distinct west–east pattern was evident. These results agree with Devall *et al.* (1991), Meldahl (1999), and Henderson & Grissino-Mayer (2008), who found positive correlations between warm season precipitation and longleaf pine radial growth.

4.2.4 Lag Relationships

Three significant lag correlations emerged when previous year's values were correlated with current years' growth measure. First, the Coastal Plain region was significantly correlated ($\alpha = 0.1$) to previous year's average June–October PDSI. The Coastal Plain region expressed no correlation to current-year average June–October PDSI, but the lagged variable was significant. Second, as with PDSI, the Coastal Plain region significantly correlated with previous year's average June–October precipitation. The Coastal Plain also significantly correlated with current year precipitation, however, when lagged it was the only significant regional correlation. Third, all regions' MXD significantly negatively correlated with previous year's average Piedmont June–October temperature. At present, no studies exist that test for a lag relationship using MXD, and I conclude both current and previous year's average temperature correlate with MXD for North Carolina longleaf pine.

4.2.5 Geographic patterns

North Carolina longleaf pine tracts did not express a distinct pattern for correlations between growth responses to climate as they did with morphological characteristics. The largest influence for morphological characteristics was edaphic conditions, and while this may also be operative for growth response, its effect is less pronounced. The Piedmont and Sandhills regions consistently expressed stronger correlations with the all climate variables, and the Sandhills region predominately expressed the strongest correlation of the three regions. Both Lodewick (1930) and Henderson and Grissino-Mayer (2008) note that sites with deep sandy soils store water poorly, drain quicker, and thus growth the response of trees on sandy soils may be less than for trees on loamier soils that can retain water for longer duration. Differing from both Parker *et al.* (2001) and Henderson and Grissino-Mayer (2008) who found that both slash and longleaf pine were more responsive to climate at more coastally sites than for sites further inland, the opposite is true for this study as inland sites appear more responsive to climate than do coastal sites.

4.2.6 Mean sensitivity and interseries correlation analysis

Both TRW IC and TRW MS expressed significant differences in means for both locational and regional testing. By region, TRW IC differed between the Piedmont and Coastal Plain and between the Sandhills and Coastal Plain, but no difference existed between the Piedmont and Sandhills regions. Therefore, at both Piedmont and Sandhills sites, longleaf pine trees are more in agreement with one another in terms of annual radial growth. Coastal Plain sites do not express this

relationship where more intersite variability exists with radial growth thus leading to lower TRW IC. By region, mean TRW MS differed between the Piedmont and Sandhills as well as the Piedmont and Coastal Plain, but no difference in means was found between the Sandhills and Coastal Plain regions. Thus, Piedmont longleaf pine are less variable year-to-year in regards to radial growth whereas Coastal Plain and Sandhills longleaf pine expressed more interannual fluctuations in radial growth.

IC is markedly lower for Coastal Plain sites, and weakest for Millis, possibly due to ecosystem harshness, where low similarity among local communities occurs in areas that have higher levels of sensitivity (Leibold *et al.*, 2004). Longleaf pine may not prefer the less fertile soils of the Coastal Plain, but rather have endured the less-favorable edaphic conditions out of necessity for regeneration and not choice (Wahlenberg, 1946). Further, this region would endure more intense hurricane force winds and have the most rapidly drained soils that may make the ecosystem 'harshest' for survival (i.e. well-spaced savannas with few trees). The trees that can endure such conditions do not express equal radial-growth with each other as an artifact of these conditions. Concurrently, lower MS for Piedmont sites may be attributed to the ability for the soil to retain moisture and lessen high/low precipitation events and annual variability. With loamier soils that can retain moisture either throughout the growing season or from season-to-season or even year-to-year, a more stable ecosystem occurs at Piedmont locations where interannual growth fluctuations are attenuated unlike the sandier, well-drained soils of the Sandhills and Coastal regions where greater annual variability of radial growth occurs.

4.2.7 A note on maximum latewood density

This study is the first at present to use MXD with longleaf pine. While studies have found positive relationships between MXD and temperature, the opposite was true for the tracts used in this study. Further studies would need to determine if this pattern is true for longleaf pine throughout its range. As multiple methods exist to measure MXD, such as X-ray densitometry or image analysis, their results have been found to be in agreement, where the more affordable image analysis can be used in place of X-ray analysis (Park & Telewski, 2007). This study used WINDENDRO image analysis software for all measurements, which uses light reflectance values as a proxy for density. Issues with this form of analysis are that areas of some samples may be providing false density values when mottled by tree resin. I did not control for this potential error, which may be evident in the low IC for MXD. While IC was low for each location (higher inter-site variability) the locations as a whole all expressed significant negative correlations with temperature.

CHAPTER V

CONCLUSIONS

This thesis presents the first observations of geographic patterns for radial growth and morphological characteristics of North Carolina longleaf pine stands. I hypothesized that there would be no difference in radial growth, tree morphology, and mean sensitivity between locations and regions. I found that morphological characteristics display a distinct geographic pattern from inland to coastal sites, and that both MS and IC and radial growth/climate relationships differ by region. The distinct geographic gradient found for tree morphology was not present in mean sensitivity or for radial growth/climate relationships.

A geographic gradient was present for standardized needle length, DBH, and height. Piedmont longleaf pine produces the longest needles, largest DBH, and the tallest trees, followed by the Sandhills region, and the weakest values were for the Coastal Plain region. This pattern is principally related to edaphic conditions, where more inland sites reside on progressively more fertile soils thus influencing tree morphology. Other influences include the roll of high wind-producing events, and/or fire frequency. These ecosystem factors help determine tree morphology assuming no changes is genotypes exist. The most significant findings for radial growth climate relationships were that LW correlated more strongly than TRW or MXD. The strongest correlations were for LW and average June–October PDSI, where all sites expressed significant positive correlations.

Temperature was the only climate variable that correlated with MXD, where negative correlations were expressed for all locations and regions. Average June–October precipitation expressed a stronger correlation with LW than for summer precipitation. Sandhills sites routinely expressed the highest correlations of the three regions, and Coastal Plain sites rarely correlated with climate variables unless lagged by one year. Lastly, MXD appears to be merging into two significantly different groups, and their division includes two groups of more inland sites that are producing denser latewood growth and more coastal sites that are producing less-dense latewood growth.

Differences for TRW MS and IC correlations existed between regions, where the Piedmont region expressed less year-to-year sensitivity than both the Sandhills and Coastal Plain regions, and both the Piedmont and Sandhills regions expressed higher IC than the Coastal Plain. I propose that these differences are influenced principally by edaphic conditions, where soil-textural properties attenuate year-to-year fluctuations in growth for the Piedmont region, and that site harshness lowers IC for the Coastal Plain region.

These results show that North Carolina longleaf pine expresses geographic patterns that are most evident in tree-morphological characteristics. As trees were found to differ regionally for morphology, MS, and radial growth/climate relationships, management and protection efforts should therefore be adjusted to suit regional ecosystem type. Longleaf pine can be an important tree for climate reconstructions, by region, as tree age can extend 200+ years, and the species is easily crossdateable and sensitive to climate. Issues I found with using North Carolina longleaf pine are that

suppression periods are present that are unrelated to monthly climatic variations, and the presence of periodic resinous and heartwood segments influence image analysis. While MXD expressed low IC and MS, its overall correlation with temperature proved significant for all sites and regions. Lastly, this study is the first to use this form of measurement with longleaf pine, and no geographic pattern was evident for MXD in North Carolina.

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